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

> **Commented [AL1]:** How about: "Historical and recent aufeis, Indigirka River basin, Russia"

*Olga Makarieva[1,2,], Andrey Shikhov[3], Nataliia Nesterova[2,4], Andrey Ostashov[2]

*[1]Melnikov Permafrost Institute of RAS, Yakutsk*
*[2]St. Petersburg State University, St. Petersburg*
*[3]Perm State University, Perm*
*[4]State Hydrological institute, St. Petersburg*
*RUSSIA*

*omakarieva@gmail.com

**Abstract:** A d~~D~~etailed spatial geodatabase of aufeis (or naled in Russian) within the Indigirka River watershed (~~, the basin area~~ 305 000 km²), Russia, was compiled from historical Russian publications (year 1958) ~~the Cadaster of aufeis of the North-East of the USSR published in 1958~~, topographic maps (year xxx), and Landsat images ~~for~~ (year 2013-2017). The aufeis ~~area share~~coverage varies from 0.26 to 1.15% in different ~~river~~ sub-basins within the Indigirka River watershed~~studied area~~. The

d~~D~~igitized historical archive (Cadaster, ~~– (~~1958) contains the coordinates and characteristics of 897 aufeis~~es~~ with total area of 2064 km². The Landsat-based identification of aufeis~~es~~ ~~for 2013-2017 allowed the description of~~included 1213 aufeis~~es~~ ~~on~~ with a total area of 1287 km². ~~The combined digital database of the aufeis is available at https://doi.pangaea.de/10.1594/PANGAEA.891036.~~ Accordingly, t~~T~~he satellite-derived total aufeis area ~~of aufeis~~ is 1.6 times less than ~~in~~ the Cadaster (1958) dataset. ~~At the same time~~However, more than 600 aufeis identified ~~by~~ from Landsat images ~~analyses~~ are missing in the Cadaster (1958) archive. It is therefore possible ~~implies~~ that the conditions for aufeis formation ~~conditions~~ may have ~~been~~ changed ~~between~~ from the mid-20th century ~~and~~ to 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. About 60% of total aufeis area are represented by top ~~presents~~ 10% of the largest ~~of the largest~~ aufeis.

> **Commented [AL2]:** Present or historical?

~~The i~~Interannual variability of ~~the~~ aufeis area for the period of 2001-2016 was ~~estimated by the example of~~ assessed at the Bolshaya Momskaya naled ~~(aufeis)~~ and ~~the~~ for a group of large aufeis (>xx km2 each) in the basin of the Syuryuktyakh River ~~for the period of 2001-2016~~. The results of analysis indicate a tendency towards an area ~~-~~decrease in ~~the area of~~ the Bolshaya Momskaya naled in recent years, while no ~~at the same time the~~ reduction Syuryuktyakh River~~in the~~ aufeis area ~~in the basin of the Syuryuktyakh River has not occurred~~was observed. The combined digital database of the aufeis is available at https://doi.pangaea.de/10.1594/PANGAEA.891036.

**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~~a ~~glaciation~~ periglacial landform~~s, standing on the same level with other types o~~ that is characteristic of many streams in cold regions ~~f snow-ice formations~~ and that ~~affecting~~ affects water exchange and economic activity (Alekseev, 1987). ~~They are distributed~~Aufeis are found in permafrost regions~~, for example,~~ such as Alaska (Slaughter, 1982), Siberia (Alekseev, 1987), Canada (Pollard, 2005), Greenland (Yde and

Knudsen, 2005) and others (Yoshikawa et al., 2007). ~~Intensification of a~~Aufeis formation ~~processes~~ can result in significant economic expenses as~~;~~ ~~they~~ aufeis may negatively affect ~~engineering constructions' sustainability~~infrastructure~~,~~ and therefore natural resource extraction ~~as well as complicate exploitation of hydro-technical and industrial constructions~~ (Aufeis of Siberia…, 1981). Moreover, the springs that often ~~,~~feed~~ing~~ aufeis may~~,~~ in some cases ~~can~~ be the only source of water ~~supply~~ for ~~inhabited localities~~remote communities (Simakov, Shilnikovskaya, 1958).

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

The main hydrological role of aufeis is the seasonal redistribution of the ~~underground~~ groundwater component of river runoff, where the ~~from~~ winter groundwater discharge is released to summer streamflow through melting of aufeis ~~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~~ of total annual streamflow at the Indigirka River (gauging station Yurty, ~~basin area~~ 51 100 km$^2$). In May, ~~it~~ aufeis melt may ~~be~~ represent 50 % of monthly total streamflow, but decreases in June to 35 % (Sokolov, 1975).

It is important to understand how climate change may impact aufeis formation ~~may be impacted by climate change~~. Aufeis are formed by a complex ~~inter~~connection between river and groundwater. ~~Currently m~~Many studies have reported 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~~ A widely accepted hypothesis for permafrost regions is that a warming climate ~~improves~~ increase the connection between surface- and groundwater ~~in permafrost areas which~~ that in turn 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~~Variation and changes in aufeis extent ~~which~~ can ~~partly~~ be assessed ~~based on the analysis of~~using remote sensing ~~data~~ techniques, where aufeis dynamics can serve as an ~~can be viewed as one~~ indicator of groundwater change~~s which~~ that ~~are~~ is otherwise difficult to ~~be~~ observe~~d naturally in remote arctic areas~~ (Topchiev, 2008; Yoshikawa et al., 2007).

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

The projections of increasing dynamics of aufeis formation under climate change are confirmed by direct observations. ~~Indeed, in~~In the ~~aufeis~~ valleys of Ulakhan Taryn and Bulus, ~~(~~central Yakutia, Russia,~~)~~ only in four~~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, however, ~~according to Yoshikawa et. al (2007), on the contrary, there are~~ no significant changes were documented in

**Commented [AL3]:** I think you need to list the last name of the author here (not the title) or alternatively, the publisher, and the publication year.

**Formatted:** Indent: First line: 0.49"

**Commented [AL4]:** Would be good to include which region this study represents.

**Commented [AL5]:** Do you mean sporadic permafrost regions?

**Commented [AL6]:** It is unclear what you are trying to say here.

the area and volume of aufeis over the past few decades or even a century (Yoshikawa et. al, 2007). Yoshikawa et. al (2007) suggested that the formation and melting of ice is less dependent on climate change and more so on the source (spring) water properties such as temperature and volume (discharge).

In 1958, Simakov and Shilnikovskaya (1958) compiled and published the mMap (scale 1:2 000 000) and the Cadasterinventory of aufeis of the North-East USSR (scale 1:2 000 000). In the last 60 yearsSince then, there has been no update onf the information on aufeis in general in this region, apart from some specific studies. In 1980-1982, the Cataloguean inventory of aufeis of in 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 onf 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. Further, the glacier science community has mapped past and recent glacier cover across the globe (GLIMS and NSIDC, 2005, updated 2017). However, at least known to the authors, there does not exist anno electronic catalogue of aufeis exists, similar to the one for. glaciers, for instance (GLIMS and NSIDC, 2005, updated 2017).

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

Developednew database—an, which includesd geographic information system (GIS) formatted files, for the updated Cadaster of aufeis in the North-East for the Indigirka River basin are is freely available for the public (Makarieva et al., 2018) and can be used both for scientific purpose and for solving practical problems, for example, such as engineering construction and water supply studies.

## 2. Research objective

The study region is the Indigirka River basin, which covering covers anthe area of 305 000 $km^2$. The largest part of theMost of the basin is a represented by highlands with a number of mountain ranges (< 3 003 m) including , the Cherskiy and Suntar-Khayata- mountainsbeing most significant, with the maximum height of up to 3 003 m.. Lower reaches of the river are in aThe lowland elevation reacheswith 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, respectively, at the Oymyakon meteorological station (726 m, 1930-2012) to -13.1 and -33.8˚C, respectively, 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 and , at the Vostochnaya station 278 mm.

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

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

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

**Formatted:** Indent: First line: 0"

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 inventory mMap (scale 1:2 000 000) and catalog 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 generalizingsummarizing quantitative work on quantitative accounting of aufeis and their features within the study territory. It The effort 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 another 442 —on the geological reports data. It is of importanceshould be noted that the parts of river valleys covered with aufeis were identified based on geomorphologic features, meaning that in some cases only the areas or river valleys with aufeis were identified but not aufeis themselves.

In the Cadaster,1958 inventory and our digitaization, 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, and area) and the dates of ice recording in aerial images (the earliest —ranging from 08.06.1944, the latest — to 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.Only vVery large and gigantic aufeis areas(> xxx $km^2$) were plotted on the Map (1958), while the all the restothers are shown just as point locations. Each aufeis on the Map (1958) has its corresponding number, under which identifier and corresponding informationit can be found in the Cadaster (1958). As noted by Simakov and Shilnikovskaya (1958), some very small aufeis (<x $km^2$) could have been missed due to their indecipherability on aerial images, as well as due to the fact that at the moment of aorir photography they might have already melted at the time of air photography. For an sampleexample of the Map's sheet (1958) for the Indigirka River upper reaches, see fig. 1.

In this studyHere, we developed 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 Our compilation contains data on 896 aufeis. The aufeis are presented in as point objects in the compiledour database. It includes areas of 808 aufeis. The total area of all the aufeis accounts for 2063.6 $km^2$ and, the areas 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 seasonal date of ice recording is August ,2, ranging from the earliest —June, 8, and the latest — to 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. (Wwhen digitized, a point was plotted in the middle of an aufeis at a topographic map).

**Commented [AL7]:** Field data?

**Formatted:** Superscript

**Formatted:** Superscript

**Commented [AL8]:** Unclear. Is it 896 or 808 aufeis in your database?

**Commented [AL9]:** Confusing. Do you mean that there was no recording date provided in the 1958 map, but only in the Cadaster (the catalog)?

**Commented [AL10]:** Unclear. Do you mean that the 1958 Cadaster/catalog was not solely based on aerial photos, but also through other sources that may not necessarily reflect aufeis coverage in ~1958?

**Commented [AL11]:** Clarify. Did you use these maps or did Grosse use these maps?

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~~ Aufeis areas were estimated by digitalization of the~~se~~ maps. Areas of the remaining aufeis were estimated with the Cadaster. ~~For 88 aufeis it~~It was not ~~im~~possible to estimate the~~ir~~ area of 88 aufeis~~area~~, as they ~~are~~ were not ~~present~~ drawn o~~i~~n the topographic maps~~,~~ and only their location, ~~areas~~ but ~~are~~ not area, was 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):

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

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). The NDSI threshold value, which is based on ~~which~~ when snow and ice surfaces are detected, ~~is taken~~were set to ~~as~~ 0.4 (Hall et al., 1995).

Apart from using NDSI~~,~~ to detect aufeis in Landsat images~~,~~ other indices ~~were also~~that have been suggested, but not used here, include: N~~n~~ormalized 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).

Formatted: Indent: First line: 0"

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, and 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 Landsat 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~~ Retrieving the thalwegs network is necessary, because almost all aufeis are located either at streams, or in immediate proximity to ~~them~~streams. Preliminary visual analysis of the images ~~allowed~~ determined ~~evaluating~~ the optimal ~~width of 1.5 km~~ buffer zone width around thalwegs to 1.5 km~~,~~ ~~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~~ an image is ~~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 ~~(~~starting in ~~from~~ mid-June~~)~~.

Morse and Wolfe (2015) suggested a new spectral index MDII for automatically distinguishing snow bodies from ice ones. However, here some of the high elevation aufeis were partially covered with snow at the image acquisition time. ~~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.~~ Instead of an automatic processing, the outlining of ~~W~~high elevation ~~hen snow cover was present,~~ aufeis ~~outline detection~~ was conducted manually when snow cover was present, as well as a manual removal of snow covered areas adjacent to aufeis. Further, during melt the aufeis often divide into several neighboring plots.

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

## 4. Results and verification

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~~In addition, 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~~two to three images of the same territory were used to reconstruct the missing objects. The total number of the aufeis, identified with the Landsat images in the Indigirka River basin, was ~~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 the~~ir~~ 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,~~ L~~l~~ess than half of the aufeis detected in Landsat 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~~.~~; and
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 instead the aufeis glades, that ~~was~~ were reported in the Cadaster (1958) ~~(which~~ and that 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 images were used~~)~~ ~~this~~ the aufeis area was significantly smaller than the typical annual 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~~ show~~n~~ that almost 60% of aufeis that is unconfirmed in the Landsat imagery and that is therefore only presented in the Cadaster ~~but not confirmed with the satellite data,~~ have an individual aufeis area less than 0.25 km$^2$ (Fig. 4-a). ~~Among the~~The confirmed aufeis~~,~~ ~~confirmed with the images, these~~ account for about 20% of the ~~(~~area ~~is~~ stated ~~according to~~in the Cadaster~~)~~. Thus, it was mainly small aufeis that were not confirmed ~~by~~ in the Landsat images. Conversely, ~~In comparison, it can be seen in~~ Fig. 4-b show that almost 60 % of the aufeis~~,~~ detected in the Landsat images ~~and~~ but not ~~confirmed by~~listed in the Cadaster~~,~~ have an area each 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~~location of aufeis. ~~As a whole~~In general, aufeis distributions by elevation as~~,~~ assessed with the Cadaster and Landsat data ~~,~~ are quite 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~~ in~~to~~ the Cadaster data than by the satellite images. This can be explained by the fact that many aufeis located at high altitudes often have a small area, so they could have been missed during the analysis of the satellite data. Further, t~~T~~hey 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~~ on the north-east slopes of the Chersky Range. Meanwhile, aufeis are almost absent in the northernmost (lowland) part of the Indigirka basin.

The head ~~reaches~~ waters of the Indigirka River, near ~~up to~~ the Yurty village, is the ~~basin~~ region with the ~~highest~~ largest aufeis ~~area~~ coverage (Table 2). Correlation between average elevation of basins and their aufeis coverage (percentage) is statistically significant~~, but less noticeable than expected~~. Among xx number of basins, the s~~S~~pearman rank correlation coefficients

**Commented [AL12]:** Please provide some information on how many basins were included.

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~~in two areas: the Bolshaya Momskaya aufeis~~ (aufeis)~~, which is located in the Moma River channel (~~according to the Cadaster its~~ area in the Cadaster is 82 km$^2$), and for ~~the~~ a group of ~~large~~ aufeis (total area in the Cadaster is 287.8 km$^2$) in the Syuryuktyakh River basin~~—~~, which is the left-bank tributary of the Indigirka River~~(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 the elvation into account. Both areas are ~~that they are~~ located at low elevations (~~:~~ Bolshaya Momskaya ~~aufeis –~~ 430 to 500 m and~~,~~ ~~the aufeis in the~~ Syuryuktyakh ~~River basin –~~ 200 to 500 m), which~~. This~~ contributes to the~~ir~~ relatively early and intensive aufeis 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~~though the satellite image was acquired ~~received in~~during the first week of May (2005)~~,~~ when aufeis melting ~~did~~ had not yet started. 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$^2$ than in 2005.~~.~~ ~~All of the above~~Accordingly, ~~might indicate the tendency of decrease in the area of~~ the Bolshaya Momskaya aufeis may have seen a decreasing trend over time in its maximum coverage.
2. The area of the largest aufeis in the Syuryuktyakh River basin in May 2014 was 78.0 km$^2$, which is ~~—~~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~~Therefore, it can be suggested that the aufeis areas within Syuryuktyakh River~~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 A~~Aaufeis detection was conducted for the 2013-2017 period using Landsat imagery with~~.~~ 1213 aufeis identified ~~with~~ having ~~the~~ a 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 results were combined in the joint Catalogue of aufeis within the Indigirka River basin available at the Pangea repository (~~at~~ https://doi.pangaea.de/10.1594/PANGAEA.891036).

~~It can be seen that~~ Recent total~~current~~ aufeis area is 1.6 times smaller than stated in the Cadaster (1958). ~~Meanwhile~~Simoultaneously, the historical Cadaster archive is lacking data on over 600 aufeis that were~~,~~ identified using satellite images. This suggests~~, on the one hand,~~ that the ~~data in the~~ Cadaster data is ~~was~~ incomplete, while~~, on the other hand, that~~ there ~~was a~~may also have been significant change in aufeis formation conditions in the last half century. One of the

**Commented [AL13]:** Can you make a stronger conclusion? For example that the total aufeis area have decreased over time, while simultaneously it appears that additional aufeis may have formed over time.

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.

## 6. References


Alekseev, V.R.: Naledi. Novosibirsk, Nauka, Moscow, 1987 (in Russian).

Alekseev, V.P.: Long-term variability of the spring taryn-aufeises. Ice and Snow, 56(1), 73-92, 2016. doi:10.15356/2076-6734-2016-1-73-92.

Alekseyev, V.R.: Cryogenesis and geodynamics of icing valleys. Geodynamics & Tectonophysics 6 (2), 171–224, 2015. doi:10.5800/GT-2015-6-2-0177.

Atlas of snow and ice resources of the world, 11 (2). Institute of geography RAS, Moscow, 270 pp., 1997 (in Russian).

Aufeis of Siberia and the Far East. Science, Novosibirsk, 244 pp. 1981. (in Russian).

Bense, V. F., Kooi, H., Ferguson, G., and Read, T.: Permafrost degradation as a control on hydrogeological regime shifts in a warming climate. Journal of Geophysical Research, 117(F03036), 2012. doi: 10.1029/2011JF002143.

Cadastre to the map of the north-east of the USSR Scale 1: 2000000. Shilnikovskaya Z.G. Central complex thematic expedition of the North-Eastern geological department. Magadan, 398 pp., 1958. (in Russian).

Catalogue of Aufeis in the Baikal-Amur Railroad Zone, 1. Aufeis in the Upper Part of the Chara River Basin. Gidrometeoizdat, Leningrad, 63 pp., 1980 (in Russian) .

Catalogue of Aufeis in the Baikal-Amur Railroad Zone, 2. Aufeis in the Muya River Basin. Gidrometeoizdat, Leningrad, 84 pp., 1981 (in Russian) .

Catalogue of Aufeis in the Baikal-Amur Railroad Zone, 3. Aufeis in the Upper Angara River Basin. Gidrometeoizdat, Leningrad. 96 pp., 1982 (in Russian).

Danielson, J.J., and Gesch, D.B.: Global multi-resolution terrain elevation data 2010 (GMTED2010): U.S. Geological Survey Open-File Report 2011–1073, 26 pp., 2011.

Explanatory note to the geocryological map of the USSR, scale 1: 2 500 000, 125 pp., 1991 (in Russian).

Ge, S., J. McKenzie, C. Voss, and Wu, Q.: Exchange of groundwater and surface-water mediated by permafrost response to seasonal and long term air temperature variation, Geophys. Res. Lett., 38, L14402, 2011. doi:10.1029/2011GL047911.

GLIMS and NSIDC: Global Land Ice Measurements from Space glacier database. Compiled and made available by the international GLIMS community and the National Snow and Ice Data Center, Boulder CO, U.S.A., doi:10.7265/N5V98602, 2005, updated 2017.

Grosse, G. and Jones, B. M.: Spatial distribution of pingos in northern Asia, The Cryosphere, 5, 13-33, 2011. https://doi.org/10.5194/tc-5-13-2011.

Hall, D K., Riggs, G.A. and Salomonson, V.V.: Development of methods for mapping global snow cover using Moderate Resolution Imaging Spectroradiometer (MODIS) data. Remote Sensing of Environment, 54, 127-140, 1995.

Kane, D. L. and Slaughter C. W.: Recharge of a central Alaska lake by subpermafrost groundwater. Nat. Acad. Sci, 38, 458-462, 1973.

Makarieva, O., Nesterova, N., Post, D.A., Sherstyukov, A. and Lebedeva, L.: Warming temperatures are impacting the hydrometeorological regime of Russian rivers in the zone of continuous permafrost. The Cryosphere (in review), 2018.

Makarieva, O., Shikhov, A., Ostashov, A., Nesterova, N.: Aufeises (naleds) of the North-East of Russia: GIS catalogue for the Indigirka River basin (Russia), PANGAEA, 2018. available at: https://doi.pangaea.de/10.1594/PANGAEA.891036.

Map of the icings of the North-East of the USSR Scale 1: 2000000. Simakov, A.S., Shilnikovskaya, Z.G. North-Eastern Geological Administration of the Main Directorate of Geology and Subsoil Protection. Central complex thematic expedition. Magadan. 1958 (in Russian).

Markov, M. L., Vasilenko, N. G. and Gurevich, E. V.: Icing fields of the BAM zone: expeditionary investigations. SPb.: Nestor-History, 320 pp., 2016 (in Russian).

Morse, P.D. and Wolfe, S.A.: Geological and meteorological controls on icing (aufeis) dynamics (1985 to 2014) in subarctic Canada. Journal of Geophysical Research: Earth Surface. 120, 1670–1686, 2015.

Pollard, W. H.: Icing processes associated with high Arctic perennial springs, Axel Heiberg Island, Nunavut, Canada, Permafrost Periglacial Processes, 16, 51 – 68, 2005.

Pomortsev, O.A., Kashkarov, E.P. and Popov ,V.F.: Aufeis: global warming and processes of ice formation (rhythmic basis of long-term prognosis). Bulletin of Yakutsk State University, 7 (2). 40-48, 2010 (in Russian).

Pomortsev, O.A., Mynbayeva, G.U. and Efremov, V.S.: Influence of aifeis on the radial growth of pines in Central Yakutia. Materials of glaciological research, 103, 47-57, 2007. (in Russian).

Reedyk, S., Woo, M.K. and Prowse, T.D.: Contribution of icing ablation to streamflow in a discontinuous permafrost area. Canadian Journal of Earth Science, 32: 13-20, 1995.

Rennermalm, A. K., Wood, E. F., and Troy, T. J.: Observed changes in pan-arctic cold-season minimum monthly river discharge, Clim. Dyn., 35(6), 923–939, 2010.

Simakov, A.S. and Shilnikovskaya, Z.G.: The map of the north-east of the USSR. A Brief Explanatory Note. The North-Eastern Geological Administration of the Main Directorate of Geology and Subsoil Protection, Magadan, 40 pp., 1958 (in Russian).

Slaughter, C. W.: Occurrence of and recurrence of aufeis in an upland taiga catchment, in: Roger J.E. Brown Memorial Volume—Proceedings of the 4th Canadian Permafrost Conference, Natl. Res. Counc. of Can., Ottawa, Ont, 182 – 188, 1982.

Sokolov, B.L.: Naleds and river runoff. Gidrometeoizdat, Leninrgad, 190 pp., 1975 (in Russian).

Surface waters resources of the USSR, 17. Leno-Indigirsky district. Gidrometeoizdat, Leninrgad, 651 pp., 1972. (in Russian).

Tananaev, N. I., Makarieva, O. M., and Lebedeva, L. S.: Trends in annual and extreme flows in the Lena River basin, Northern Eurasia. doi: 10.1002/2016GL070796, 2016.

Tolstikhin, O.N.: Naleds and ground waters in the North-East of the USSR. Science, Novosibirsk, 164 pp., 1974 (in Russian).

Topchiev A.G.: Methods of aerospace monitoring of aufeis geosystems and underground water of cryolithozone. Systems and means of informatics, 2008, 18 (3), pp. 304-327 (in Russian)

US Geological Survey Server: http://earthexplorer.usgs.gov, last access: 1 August 2018.

Walvoord, M. A., Voss C. I. and Wellman T. P.: Influence of permafrost distribution on groundwater flow in the context of climate-driven permafrost thaw: Example from Yukon Flats Basin, Alaska, United States, Water Resour. Res., 48, W07524, 2012. doi:10.1029/2011WR011595.

Walvoord, M. A. and Kurylyk, B. L.: Hydrologic Impacts of Thawing Permafrost—A Review. Vadose Zone Journal, 15 (6), 2016. doi: https://doi.org/10.2136/vzj2016.01.001.

Yde, J. C., and Knudsen, N. T. Observations of debris-rich naled associated with a major glacier surge event, Disko Island, west Greenland, Permafrost Periglacial Processes, 16, 319 – 325, 2005.

Yoshikawa, K., Hinzman, L.D., and Kane, D.L.: Spring and aufeis (icing) hydrology in Brooks Range, Alaska, Journal of Geophysical Research: Biogeosciences, 112, 1–14, 2007.

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

| Data source | Matching aufeis number and ~~(~~area (km²) | Not confirmed aufeis number and ~~(area~~ area (km²) |
|---|---|---|
| Cadaster (1958) | 634 (1905.~~,~~0) | 262 (158.~~,~~6) |
| Landsat | 611 (1037.~~,~~0) | 602 (250.~~,~~4) |

Table 2 Assessment of aufeis area ~~share~~ coverage (percentage) in the sub-basins within the Indigirka River ~~basin~~ watershed through ~~by~~ the Cadaster and Landsat data.

| River ~~– outlet~~ | Area, km² | Average elevation, m a.s.l. | % ~~of~~ aufeis ~~by~~ coverage (Cadaster) | % ~~of~~ aufeis coverage ( ~~by~~ Landsat) |
|---|---|---|---|---|
| Suntar R~~r~~iver – ~~riv.~~ Sakharinya River mouth | 7680 | 1460 | 0.97 | 0.78 |
| Elgi – 5.~~0~~ km upstream of the ~~river~~ Artyk-Yuryakh River 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 area~~s~~ changes, 2001-2016.

| Bolshaya Momskaya aufeis | | The group of aufeis in the Syuryuktyakh River basin | |
|---|---|---|---|
| Imagery date | Aufeis area, km² | Imagery date | Aufeis area, km² |
| 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 |

**Commented [AL14]:** Perhaps these dates are switched?

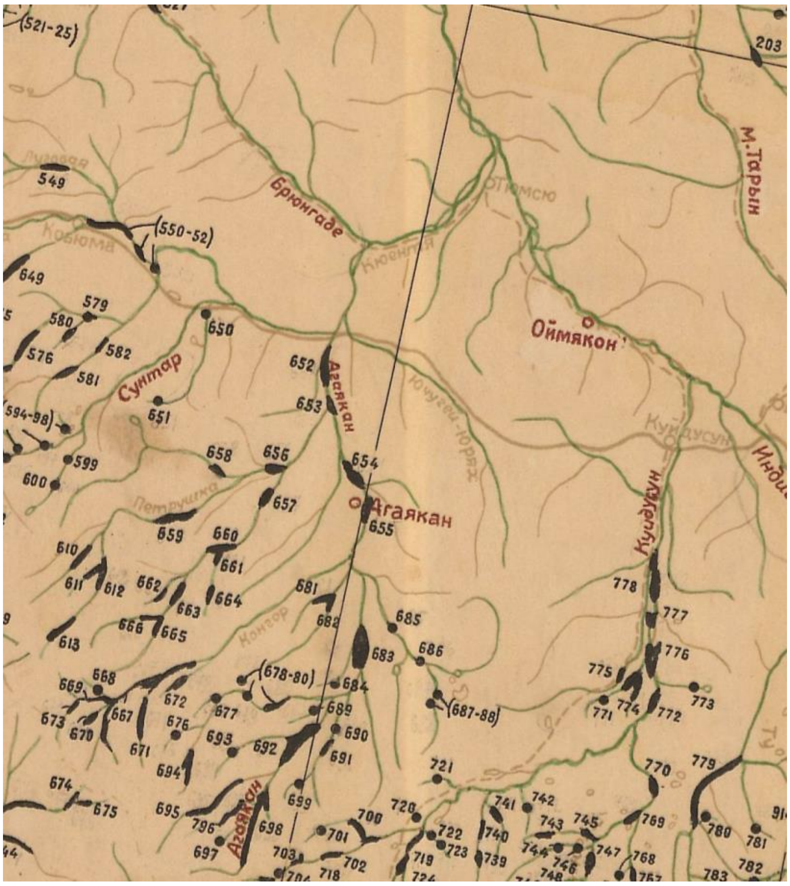


Fig. 1 Subset ~~from~~ of the ~~Map of~~ aufeis Map of the North-East of the USSR from 1958 (sheet 7, upper reaches of the Indigirka River – the basins of the rivers Suntar, Agayakan and Kuydusun).

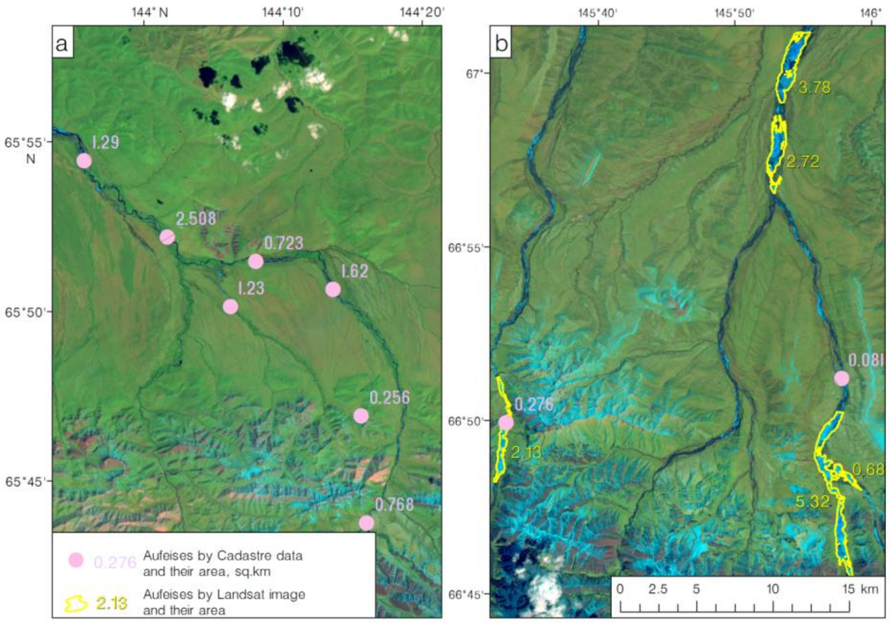


Fig. 2 Difference between aufeis location according to the Cadaster and satellite data: a) – aufeis are absent in the image but present in the Cadaster (Landsat-8 image of 18.06.2017); b) – aufeis are absent (or their area is understated) in the Cadaster but present in the image (Landsat-8 image of 30.05.2016).

**Commented [AL15]:** Spelling of aufeis in the figure.

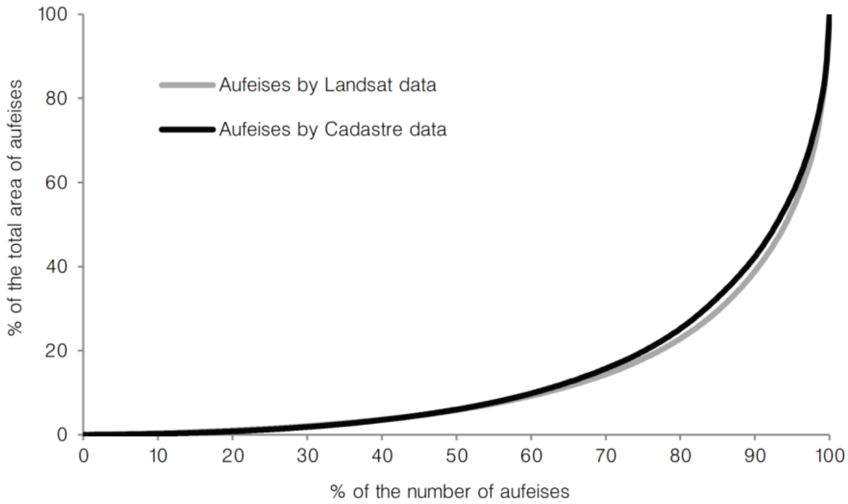


Fig. 3 Lorenz curves illustrating aufeis area distribution according to the Cadaster and Landsat data

**Commented [AL16]:** I think you write one aufeis and several aufeis (no aufeises).

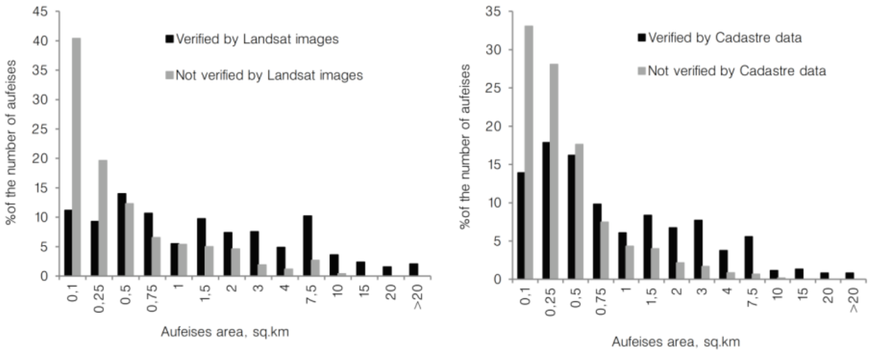


Fig. 4 Aufeis area distribution: a) – according to the Cadaster data, confirmed and not confirmed by Landsat images, b) – according to Landsat images, confirmed and not confirmed by the Cadaster.

Commented [AL17]: Spelling of aufeis in figure.

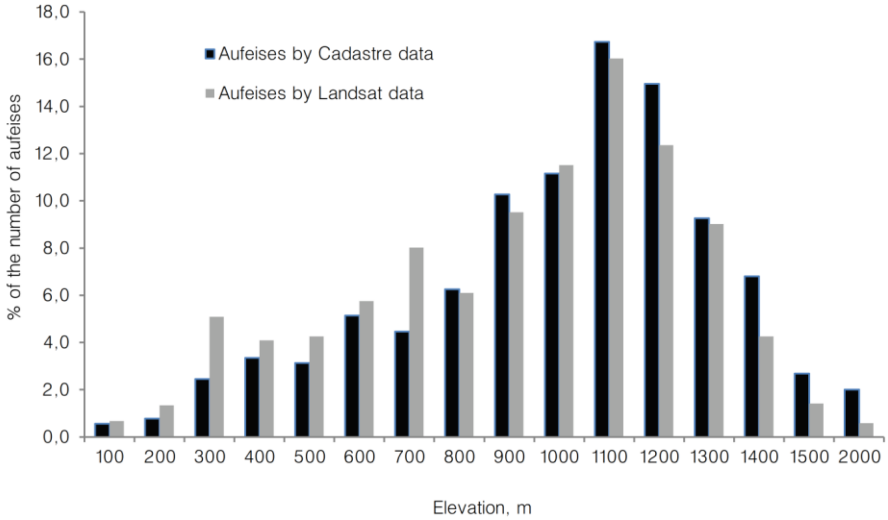


Fig. 5 Aufeis distribution by elevation within the Indigirka River basin.

Commented [AL18]: Spelling of aufeis

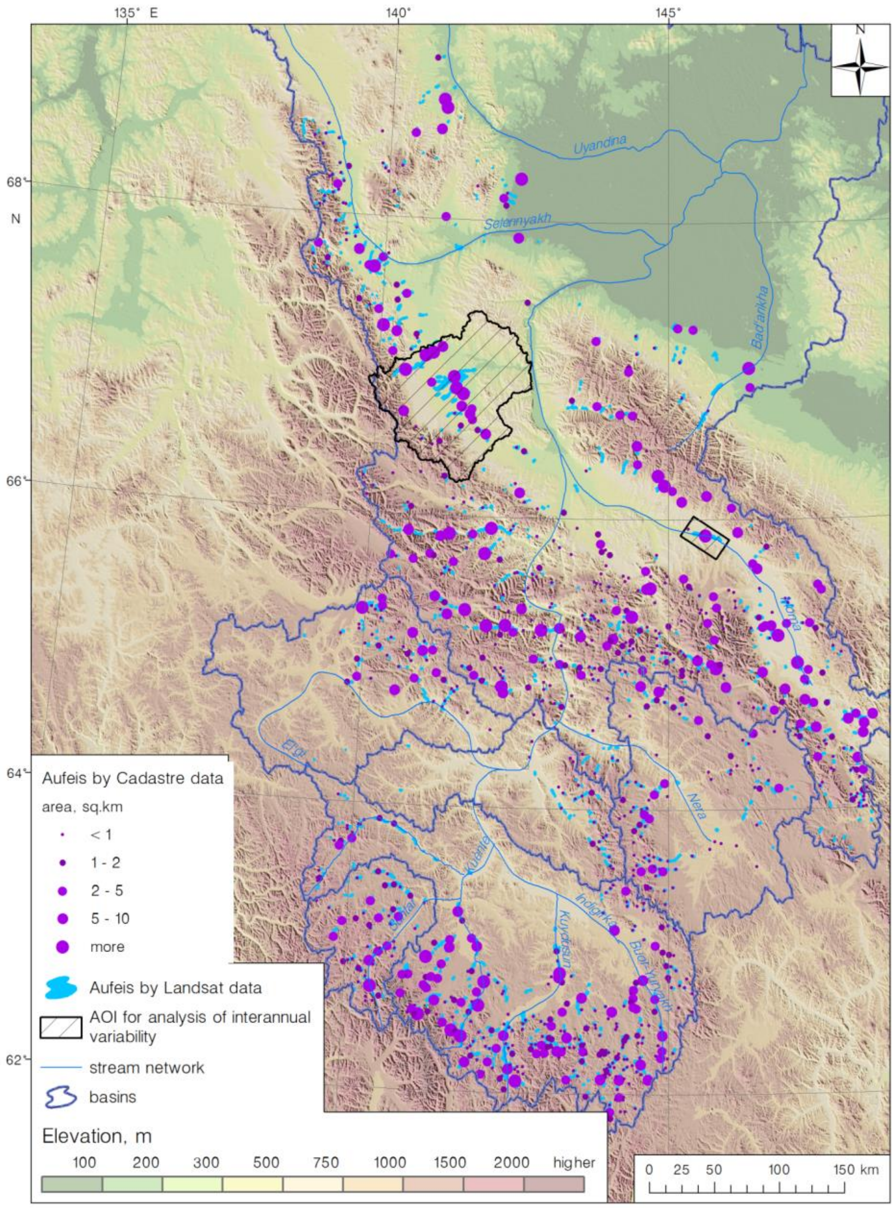


Fig. 6 Aufeis in the Indigirka River basin according to the Cadaster and Landsat images. Black outlines with section lining represent the zones where aufeis area interannual variability was assessed.