

Reviewer 1

This is a unique temporal data collection of aufeis data in the Indigirka river basin, Russia. Aufeis or naleds deposits are thick accumulations of ice that form during winter along stream and river valleys in arctic and subarctic regions impacting hydrology and geomorphology of these regions. The authors compiled and standardized historical data on aufeis deposits in the Eastern Siberian Indigirka river basin from a historical Russian National cadastre complementing data using historical topographical maps and added a new data set on aufeis derived from Normalized Differential Snow Index (NDSI) index calculation using Landsat 8 OLI sensor data. The authors cross-referenced the historical and the present-day data collection. The data collection is organised as a Geographic Information System GIS data base including data on location, area coverage, elevation, time stamp, source of data in form of attribute tables and the aufeis objects in the data format of GIS point and polygonal vector layers. The Indigirka aufeis catalogue is published on PANGAEA in the form of a GIS data base with a helpful and detailed read-me description of the attribute tables. The data collection will be of interest to hydrologists, climatologists, geomorphologists, cryologists and social science. The authors document in the manuscript the generation of the historical and the modern date data sets and its meta data characteristics. The authors also discuss the validity of data, the cross referencing between historical and nowadays aufeis deposits and reasons for mismatches in areal coverage and locations and possible changes due to climate.

Comment: The paper is in general clearly written with many details provided. However, the article including the title, the PANGAEA data publication including title, abstract and the metadata description need to be carefully edited for English before acceptance of the paper. The data compilation process and metadata is not thoroughly and clear enough shown and explained and the GIS data require further standardization and optimization to make them reusable.

Technical issues, GIS data: 1) the GIS shape files contain different projections: The GIS data catalogue is published in PANGAEA as an ARCGIS project data base. The downloaded data base is user friendly readable and usable using the proprietary GIS software ARCGIS. ARCGIS licenses are costly and many user groups may use open source GIS or other geodata software packages. Using ARCGIS software the shape-files are automatically but only virtually brought to the same projection. The GIS shape files are also readable and reusable using open source geodata software packages – however the 2 data collections have different projections (the aufeis kadastr shape file contains the projection "Asia_North_Lambert_Conformal_Conic" the aufeis Landsat shape file not). This requires users of these datasets who are using free software packages to reproject the shape files to a common projection prior to being able to use the data sets together. Please standardise the shapefiles using one projection

Response: We prepared the data according to the comments. The GIS database contains the data of aufeis in two forms: ArcGIS 10.1/10.2 and Qgis 3* projects. All data and projects have WGS 1984 coordinate system (without projection). ArcGIS and Qgis projects contain two layers, such as Aufeis_kadastr (historical aufeis data collection, point objects) and Aufeis_Landsat (satellite-derived aufeis data collection, polygon objects).

Comment: 2) the GIS attribute files do not contain self-explanatory attribute names: The Indigirka aufeis data collection is a highly valuable data set, specifically also because the authors are using cross reference indices to link the data sets. This needs to be made more clear in the naming and cross-referencing of the attribute names. E.g., the cross reference index should be also named accordingly, e.g. as cross index similarly in both attribute tables, not named ID in the aufeis_Landsat data set and named PolygonID in the aufeis kadastr data set. Naming of similar attributes should be standardized between the data sets, e.g. the attribute area in sqkm. Suggestions on attribute naming is attached as supplement. Please consider to change attribute names to more self-explanatory names.

Response: We followed the suggestions on enhancing attribute naming as much as possible. Though due to the limited length of the name we could not do it in all namings. See the Tables 1 and 2 in the paper. The PANGAEA database is updated accordingly.

Comment: The data set can also be uploaded in Google Earth with visualization of the data objects and the metadata and will be by this very easy re-usable if attribute naming and cross-referencing between the 2 data sets will be made as self-explanatory as possible.

Response: We uploaded the database into Google Earth and added the files to PANGAEA database. Additionally the watershed borders which are mentioned in the analysis in the paper added in Google earth format.

Comment: 3) consistency of published GIS data with manuscript content: Authors show in the manuscript assessments of both data sets – cadastre derived and satellite derived related to elevation. The attribute elevation is however missing in the attribute table of aufeis_Landsat. Consider to add information on elevation into the attribute table of the aufeis Landsat data set.

Response: The attribute Elevation is added to Landsat data set (See also Table 2 in the paper).

Comment: Issues, data publication on PANGAEA: Title: aufeis is the plural form of aufeis, the plural form aufeises does not exist.

Response: We changed the title of the database to “Aufeis (naleds) of the North-East of Russia: GIS catalogue for the Indigirka River basin (Russia)”

Comment: Abstract: The abstract should be extended to contain more technical information on the data. Authors should inform the users that the data download will consist of a complete ARCGIS project containing 2 different feature GIS shape files with historical and the nowadays aufeis data collection. The authors can add short information in the abstract on how the data were generated. Very useful for future users of the GIS data is to provide in the abstract text information on the projection of the GIS data collection – this is sometimes handy for reading data in in some open source geodata software packages.

Response: We extended the abstract as the following.

The GIS database contains the data of aufeis (naleds) in the Indigirka River basin (Russia) from historical and nowadays sources, and complete ArcGIS 10.1/10.2 and Qgis 3* projects to view and analyze the data. All data and projects have WGS 1984 coordinate system (without projection). ArcGIS and Qgis projects contain two layers, such as Aufeis_kadastr (historical aufeis data collection, point objects) and Aufeis_Landsat (satellite-derived aufeis data collection, polygon objects). Historical data collection is created based on the Cadastre of aufeis (naleds) of the North-East of the USSR (1958). Each aufeis was digitized as point feature by the inventory map (scale 1:2 000 000), or by topographic maps. Attributive data was obtained from the Cadastre of aufeis. According to the historical data, there were 896 aufeis with a total area 2063.6 km² within the studied basin. Present-day aufeis dataset was created by Landsat-8 OLI images for the period 2013-2017. Each aufeis was delineated by satellite images as polygon. Cloud-free Landsat images are obtained immediately after snowmelt season (e.g. between May, 15 and June, 18), to detect the highest possible number of aufeis. Critical values of Normalized Difference Snow Index (NDSI) were used for semi-automated aufeis detection. However, a detailed expert-based verification was performed after automated procedure, to distinguish snow-covered areas from aufeis and cross-reference historical and satellite-based data collections. According to Landsat data, the number of aufeis reaches 1213, with their total area about 1287 km². The difference between the Cadastre (1958) and the satellite-derived data may indicate significant changes of aufeis formation environments.

Comment: The authors could add an overview figure of the data set as additional information.

Response: We uploaded the database into Google Earth and added the files to PANGAEA database. Additionally the watershed borders which are mentioned in the analysis in the paper added in Google earth format. We also added overview figure to the database.

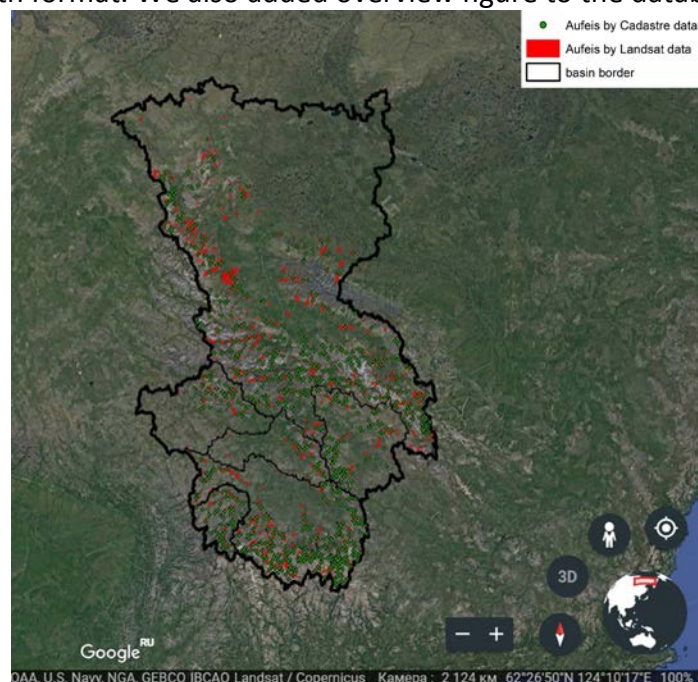


Fig. Google Earth aufeis database overview

Comment: Published data: the authors published the GIS project with 2 feature layer data and the 2 data collections also in form of ASCII files and a detailed read me word file documenting

the attribute tables. Information on the GIS project itself in the read-me file is missing: e.g., information on the format (ARCGIS) and projection.

Response: We added the missing information.

Comment:- Issues, manuscript:

General: aufeis is the plural form of aufeis, the plural form aufeises does not exist. Authors could also consider to sometimes refer to aufeis deposits in the manuscript if this fits.

Response: We fixed wrong plural form through the text and figures.

Comment: Authors could refer to the cadastral map instead of map throughout the text, also to better distinguish for the reader the cadastral map from topographic map forms.

Response: The expression "Cadastral map" has been introduced starting from Line 133 after the description of the Cadsatre.

Comment: Abstract: The authors should enrich the abstract with much more information on the technical generation and technical contents of the data set and with less discussion on changed areas and potential reasons that would be kind out of scope and not the focus of this ESSD publication. A great meta data information in this data collection is the cross-reference index enabling users of this data set to link and compare these very different 2 data set types: the historical and the nowadays aufeis data sets.

Response: Short information on Landsat-based aufeis detection and cross-reference index is added in the abstract.

Lines 13-16: Identification of aufeis by late-spring Landsat images was performed with a semi-automated approach according to Normalized Difference Snow Index (NDSI) and additional data. Then, a cross-reference index was set for each aufeis, to link and compare historical and satellite-based aufeis data sets.

Comment: keywords: reconsider the keywords, e.g., aufeis, Indigirka, Bolshaya Momskaya, Land-sat, NDSI, cadastre, cadastral map;

Response: We changed the keywords according to the comment.

Line 34-35. Keywords: aufeis, Indigirka, Landsat, NDSI, Cadastre, Cadastral map, Bolshaya Momskaya aufeis

Comment: Introduction: authors should provide an explanation what is aufeis in the first sentences of the introduction. That aufeis are thick accumulations of ice that form during winter along stream and river valleys in arctic and subarctic regions.

Response: We provided the explanation.

Lines 38-40. Aufeis (naleds in Russian, icings in English) are the accumulations of ice that are formed by freezing underground, surface and atmospheric waters on the surface of the earth or ice along streams and river valleys in arctic and subarctic regions.

Comment: 2 Research objective: this subtitle is misleading as the motivation of this study and data set compilation is already well introduced by the authors in the introduction chapter. This chapter describes the study region. Please add an overview figure with the geographical setting of the Indigirka river basin and the extent of the data set in relation to Eastern Siberia. E.g., Figure 6 is already zoomed in to provide this information.

Response: We changed this subtitle to Study region (line 105). An overview figure with the geographical location of the Indigirka river basin is added (Line 484).

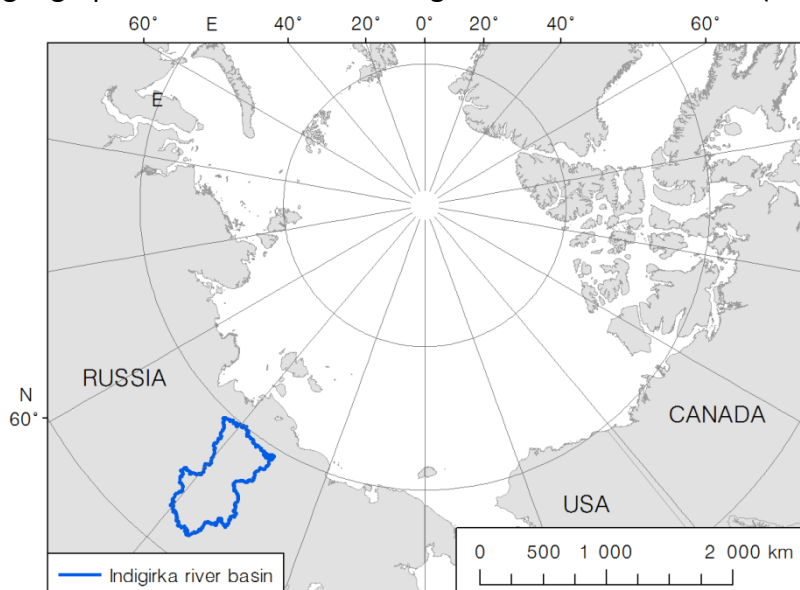


Fig. 1 Geographical location of the Indigirka river basin

Comment: 3 Material and Methods: The authors should add the tables from the published readme file in the respective subsections 3.1 and 3.2.

Response: Table 1 and 2, which contain the structure of the GIS database of aufeis according to Cadastre and Landsat images has been added.

Comment: The authors should add flow charts to make their data processing steps more clear in the in the respective subsections 3.1 and 3.2. For example the role of the thalweg creation remains unclear to the reader.

Response: Thalweg creation was an essential step of semi-automated separation of the aufeis from snow-covered areas by late-spring Landsat images. Indeed, almost all aufeis are located either at streams or thalwegs, or in immediate proximity to them. On the contrary, the snow cover in late spring mainly remains on mountains ridges and other areas with high altitude, e.g. relatively far from thalwegs. Based on the preliminary analysis of aufeis location in relation to created network of thalwegs, we estimated, that 1.5 km wide buffer zone around the thalwegs covers almost all aufeis. So, snow and ice covered areas, which are located outside this buffer, are excluded from the further analysis.

The explanation has been added.

Line 213-223: Aufeis detection algorithm was realized in ArcGIS with the help of the ModelBuilder application. Apart from the Landsat images, the digital terrain model (DTM) GMTED2010 (Danielson and Gesch, 2011) with the spatial resolution of 250 m was used to build a network of thalwegs within the study basin. This is essential for semi-automated separation of the aufeis from snow-covered areas by late-spring Landsat images. Indeed, almost all aufeis are located either at streams or thalwegs, or in immediate proximity to them. On the contrary, the snow cover in late spring mainly remains on mountains ridges and other elevated locations, e.g. relatively far from thalwegs. Based on the preliminary analysis of aufeis location in relation to created network of thalwegs, we found, that 1.5 km wide buffer zone around the thalwegs covers almost all aufeis. So, snow and ice covered areas, which are located outside this buffer, are excluded from the further analysis.

The ASTER GDEM data set needs to be introduced and explained as the meta data information on elevation is taken from this digital data set. Also for the Land-sat derived dataset? This does not become clear to the reader.

We added the information about DEM.

Line 214-216: Apart from the Landsat images, the digital terrain model (DTM) GMTED2010 (Danielson and Gesch, 2011) with the spatial resolution of 250 m was used to build a network of thalwegs within the study basin.

Comment: 3.2. The level of the USGS Landsat data product that was used remains unclear. The authors did not use the Landsat T1 Level2 (L2) that is the surface reflection coefficient already? Did the authors use the Landsat T1 Level1 data products that are terrain-corrected (T1) and Top-of-Atmosphere radiances (L1)? Because authors refer to brightness?

Response: We used Landsat 8 collection 1 Level1T (terrain-corrected) data products. The explanation has been added. Line 204-205: We used Landsat 8 collection 1 level-one terrain-corrected product (L1T) with radiometric and geometric corrections

Comment: The authors describe: Preprocessing of the images (transformation brightness into reflection coefficient) was performed with the use of Semi-Automatic Classification Plugin module in QGIS 2.18. Does it mean that an atmospheric correction was performed to surface reflection coefficient? Which type of atmospheric correction was performed to come to the surface reflection coefficient / surface reflectance?

Response: Preprocessing of the images was performed with the use of Semi-Automatic Classification Plugin module (QGIS 2.18). It includes the calculation of surface reflectance and atmospheric correction by Dark Object Subtraction (DOS1) image-based algorithm, described by (Chavez, 1996). The explanation has been added.

Line 209-212: Preprocessing of the images was performed with the use of Semi-Automatic Classification Plugin module (QGIS 2.18). It includes the calculation of surface reflectance and atmospheric correction by Dark Object Subtraction (DOS1) image-based algorithm, described by (Chavez, 1996).

Comment: 3.3 A good description of the cross reference between the aufeis deposits in the historical aufeis data collection and the nowadays data collection is missing. Authors can consider to add a short sub-paragraph 3.3. It would be helpful for re-using the data set if authors put some details here, e.g. highlight that there is the cross reference ID in both attribute tables.

Response: The sub-paragraph is added

Line 256-271: Cross-verification of aufeis data collections by the Cadastre (1958) and satellite imagery was performed in two steps. At the first step, we found closest aufeis in the Landsat-derived dataset for each aufeis from the Cadastre data, if the distance between them was less than 5000 m. The determination of search radius is based on a preliminary analysis of the aufeis locations by the Cadastre in relation to Landsat-based dataset. As a result, the cross index (identifier of the closest aufeis in the Landsat-derived dataset) and minimum distance (m) to the closest aufeis were determined for aufeis from Cadastre. For Landsat-based dataset, the cross index is the key field for the reference to the dataset from Cadastre. At the second step, a full manual verification was performed to found the mistakenly interrelated aufeis. For example, if the closest aufeis from Cadastre and from Landsat-based dataset were at a distance of less than 5000 m, but in different thalwegs, they were considered as different (unrelated) aufeis. In total, 260 aufeis from Cadastre were not verified by Landsat images. For them, the NoData value (-9999) was set in the Cross Index and Distance fields of attributive table (see Table 1 with the structure of GIS dataset from Cadastre).

Comment: 4 Results and verification: The chapter does not seem to describe or focus on verification?

Response: We changed to subtitle "Results" (line 273)

Comment: In the first section of 4 Results the authors very interestingly assess the linkages and differences between the data sets – this could become a subchapter 4.1. with a title relating to the comparison of the historical to the modern data collection. All of the above points can be addressed with minor corrections, just a few sentences or less.

Response: We corrected the title to "Comparison of the historical and modern data collection" (line 274)

Comment: consider adding a Discussion chapter with a short discussion about the usability of this data set on aufeis area growth or decline, could be one outcome of your study on the variability to assign higher variability and lower accuracy to the extraction of the aufeis area at lower elevation? Would it be possible to assign different reliability (consistency of measurement) levels for the representativeness of the derived aufeis area? e.g. a coding of robustness 0 to 3 or a type of error code based on the authors regional and thematic expertise, related to elevation (as the authors describe that too low elevation not as good because early aufeis melt and higher variability, too high not as good because too late snow melt?).

Response: We added the Discussion section. We do not think we may assign relative reliability; instead some general analysis of the data limitations (lines 367-421) is presented.

Reviewer 2 Anna Liljedahl

The comments were sent in the form of doc document. So we have combined them here.

Comment: Suggestion to change the title to “Historical and recent aufeis, Indigirka River basin, Russia”

Response: Accepted. We changed the title.

Comment: In the abstract to specify present or historical aufeis are located in the elevation band of 1000-1300 m.

Response: Specified. Line 25: Most present and historical aufeis are located in the elevation band of 1000 – 1200 m.

Comment: Suggestion to the reference. I think you need to list the last name of the author here (not the title) or alternatively, the publisher, and the publication year.

Response: We changed the reference as the following: (Aufeis of Siberia..., Nauka, 1981) – Line 46

Comment: The question to the reference (Alekseev, 2016) - Would be good to include which region this study represents.

Response: Line 74-77 Expanded the sentence as the following: However, the same author (Alekseev, 2016) states a general tendency to the decrease of aufeis volume for the last 50-60 years in some aufeis-affected areas of Russia such as Baikal region, South Yakutia, Kolyma region, Eastern Sayan Mountains, following the increase of global and local air temperature.

Comment: Unclear. Is it 896 or 808 aufeis in your database?

Response: Lines 156-157. Clarified. Our compilation contains data on 896 aufeis. The aufeis are presented as point objects in our database. The areas are specified only for 808 aufeis.

Comment: Confusing. Do you mean that there was no recording date provided in the 1958 map, but only in the Cadastre (the catalog)?

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

Response: Lines 162-166. Clarified. The dates of ice recording for the remaining 34 % of the aufeis were not described, meaning that aufeis detection could be carried out based not on the visible ice presence at the aerial images but on geomorphological features of river valleys. Therefore, the Cadastre might as well contain data on old aufeis glades, where the aufeis themselves were absent.

Comment: Clarify. Did you use these maps or did Grosse use these maps?

Response: Lines 167-172. Clarified. Spatial positioning of the Cadastral 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 of 1:200 000 scale were 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.

Comment: Please provide some information on how many basins were included in correlation analysis.

Response: Lines 328-330. Clarified. Among 6 basins, the Spearman rank correlation coefficients between the basin average elevation and aufeis percentage are 0.71 and 0.77, the aufeis percentage assessed with the Cadastre and satellite data respectfully.

Comment: 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.

Response: We added the discussion section (lines 367-421) which shows the limitations of the datasets. Also we added the analysis of area reduction of large and giant aufeis.

We do not think we have the complete evidence for strong conclusion. In Conclusion section we are rather cautious:

Lines 436-439: The analysis of large and giant aufeis seems to indicate that there has been a significant decrease in aufeis area over the period of last 70 years. Additional analysis of historical aerial photography data could help to clarify the issue of aufeis area decline trend since the middle of the 20th century to the present.

Comment: Spelling of aufeis through the text and in the figures

Response: Corrected in the text and figures.

Historical and recent aufeis, the Indigirka river basin (Russia)

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Abstract: A detailed spatial geodatabase of aufeis (or naleds in Russian) within the Indigirka River watershed (305 000 km²), Russia, was compiled from historical Russian publications (year 1958), topographic maps (years 1970–1980's), and Landsat images (year 2013-2017). Identification of aufeis by late-spring Landsat images was performed with a semi-automated approach according to Normalized Difference Snow Index (NDSI) and additional data. After this, a cross-reference index was set for each aufeis, to link and compare historical and satellite-based aufeis data sets.

The aufeis coverage varies from 0.26 to 1.15% in different sub-basins within the Indigirka River watershed. The digitized historical archive (Cadastre, 1958) contains the coordinates and characteristics of 896 aufeis with total area of 2064 km². The Landsat-based dataset included 1213 aufeis with a total area of 1287 km². Accordingly, the satellite-derived total aufeis area is 1.6 times less than the Cadastre (1958) dataset. However, more than 600 aufeis identified from Landsat images are missing in the Cadastre (1958) archive. It is therefore possible that the conditions for aufeis formation may have changed from the mid-20th century to the present.

Most present and historical aufeis are located in the elevation band of 1000 – 1200 m. About 60% of total aufeis area is represented by just 10% of the largest aufeis. Interannual variability of aufeis area for the period of 2001-2016 was assessed for the Bolshaya Momskaya aufeis and for a group of large aufeis (11 aufeis with a areas from 5 to 70 km²) in the basin of the Syuryuktyakh River. The results of this analysis indicate a tendency towards an area decrease in the Bolshaya Momskaya aufeis in recent years, while no reduction in Syuryuktyakh River aufeis area was observed.

The combined digital database of the aufeis is available at <https://doi.pangaea.de/10.1594/PANGAEA.891036>.

Keywords: aufeis, Indigirka, Landsat, NDSI, Cadastre, Cadastral map, Bolshaya Momskaya aufeis

1. Introduction

Aufeis (naleds in Russian, icings in English) are accumulations of ice that are formed by freezing underground and surface waters on the surface of the earth or ice along streams and river valleys in arctic and subarctic regions. They affect water exchange and economic activity (Alekseev, 1987). Aufeis are found in permafrost regions such as Alaska (Slaughter, 1982), Siberia (Alekseev, 1987), Canada (Pollard, 2005), Greenland (Yde and Knudsen, 2005) and others (Yoshikawa et al., 2007). Aufeis formation can result in significant economic expenses as aufeis may negatively affect infrastructure and therefore natural resource extraction (Aufeis of Siberia..., Nauka, 1981). Moreover, the springs that often feed aufeis may in some cases be the

47 only source of water for remote communities (Simakov, Shilnikovskaya, 1958). In Russia, aufeis
48 are found in the North-East, Transbaikal region, Yakutia, and West Siberia. Sokolov (1975)
49 estimated that the total aufeis water storage in Russia to be at least 50 km³, which approximately
50 equals the Indigirka River total annual streamflow.

51 The main hydrological role of aufeis is the seasonal redistribution of the groundwater
52 component of river runoff, where the winter groundwater discharge is released to summer
53 streamflow through melting of aufeis (Surface water resources, 1972). In most cases, the share of
54 the aufeis component in a river's annual streamflow accounts for 3-7%, reaching 25-30% in
55 particular river basins with an extremely large proportion of aufeis (Reedyk et al., 1995; Kane &
56 Slaughter, 1973; Sokolov, 1975). The most significant water inflow from aufeis melting takes
57 place in May-June (Sokolov, 1975). For example, the share of the aufeis flow accounts for more
58 than 11% of total annual streamflow at the Indigirka River (gauging station Yurty, 51 100 km²).
59 In May, aufeis melt may represent 50% of monthly total streamflow, but decreases in June to
60 35% (Sokolov, 1975).

61 It is important to understand how climate change may impact aufeis formation because
62 warming has been observed in this region causing the transformation of permafrost
63 (Romanovsky et al., 2007), glaciers reduction (Ananicheva, 2014) and hydrological regime
64 changes (Bring et al., 2016; Makarieva et al., 2018). Aufeis are formed by a complex connection
65 between river and groundwater. Many studies have reported the increase of minimum flow in
66 Arctic rivers (Rennermalm and Wood, 2010; Tananaev et al., 2016), including those where
67 aufeis are observed in abundance (Makarieva et al., 2018, in review). A widely accepted
68 hypothesis for permafrost regions is that a warming climate increases the connection between
69 surface- and groundwater that in turn leads to the increase of streamflow, both in cold seasons
70 and in annual flow (Bense et al., 2012; Ge et al., 2011; Walvoord et al., 2012; Walvoord and
71 Kurylyk, 2016). Variation and changes in aufeis extent can be assessed using remote sensing
72 techniques, where aufeis dynamics can serve as an indicator of groundwater change that is
73 otherwise difficult to observe (Topchiev, 2008; Yoshikawa et al., 2007).

74 The understanding of how aufeis respond to a warming climate varies. Alekseev (2016)
75 suggests three to 11 year up and down cycles of aufeis maximum annual size, which may vary
76 up to 25-30% in comparison with long-term average values. However, the same author
77 (Alekseev, 2016) states a general tendency to the decrease of aufeis volume for the last 50-60
78 years in some aufeis-affected areas of Russia such as the Baikal region, South Yakutia, Kolyma
79 region, Eastern Sayan Mountains, following the increase of global and local air temperature.

80 Some authors suggest that degradation of permafrost in the discontinuous and sporadic
81 permafrost regions will lead to the decrease of the number of aufeis and even an almost complete
82 disappearance. Meanwhile, in the zone of continuous permafrost in North-East Siberia, a climate
83 warming of 2-3 °C is not projected to lead to significant changes in permafrost extent, but will
84 increase the number and size of both through- and open taliks by the end of the 21st century
85 (Pomortsev et al., 2010). Such a scenario may result in the reduction of area of large aufeis and
86 formation of new small aufeis (Pomortsev et al., 2010).

87 In Alaska as well, no significant changes were documented in the area and volume of aufeis
88 over the past few decades or even a century (Yoshikawa et. al, 2007). They suggested that the
89 formation and melting of ice is less dependent on climate and more so on the source (spring)
90 water properties such as temperature and volume.

91 In 1958, Simakov and Shilnikovskaya (1958) compiled and published a map inventory of
92 aufeis of the North-East USSR (scale 1:2 000 000). Since then, there has been no update on the
93 information on aufeis in this region, apart from some specific studies. In 1980-1982, an
94 inventory of aufeis in the zone of the Baikal-Amur Mainline was published (Catalog of
95 Aufeis..., 1980, 1981, 1982). Markov et al. (2017) summarized the results of field studies on
96 aufeis in the southern mountain taiga of Eastern Siberia from 1976 to 1983. Grosse and Jones
97 (2011) compiled the spatial geodatabase of frost mounds (or pingos) for northern Asia from
98 topographic maps. Further, the glacier science community has mapped past and recent glacier

99 cover across the globe (GLIMS and NSIDC, 2005, updated 2017). However, as far as the authors
100 are aware, no electronic catalogue of aufeis exists.

101 The aim of this study is to update the inventory of aufeis in the North-East of Russia using
102 Landsat images, as well as to develop an electronic catalogue, which will contain data on historic
103 and current location and characteristics of aufeis. Here we present work that has been completed
104 for the Indigirka River basin (down to the Vorontsovo gauging station, 305 000 km²).

105 The new database, which includes geographic information system (GIS) formatted files, is
106 freely available (Makarieva et al., 2018) and can be used both for both scientific purposes and
107 for solving practical problems such as engineering construction and water supply studies.

108 **2. Study region**

109 The study region is the Indigirka River basin, which is located in Northeastern Siberia and
110 covers an area of 305 000 km² (Fig. 1). Most of the basin is represented by highlands with a
111 number of mountain ranges (< 3 003 m) including the Cherskiy and Suntar-Khayata mountains.
112 The lowland elevation reaches heights up to 350 m.

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

119 The Indigirka River basin is located in the zone of continuous permafrost. Permafrost
120 depth can reach 450 m in the mountains, up to 180 m in river valleys and intermountain areas,
121 with taliks found in river beds and fractured deposits. The hydrogeological regime is affected by
122 the active layer, which varies from 0.3 m to over 2 m (Explanatory note ..., 1991). The river
123 runoff regime is characterized by high snowmelt freshet, summer-autumn rainfall floods, and
124 low winter flow. In winter, small- and medium-sized rivers completely freeze. Freshet starts in
125 May-June and lasts for approximately 1.5 months. Melt waters from aufeis, glaciers, and snow
126 patches add to the river discharge in summer.

127 In total, about 10 000 aufeis with a total combined area of about 14 000 km² (Sokolov,
128 1975) are known in North-East Russia. The watershed area covered by aufeis varies from 0.4 to
129 1.3%, reaching 4% in some river basins (Tolstikhin, 1974). Most aufeis are of ground water
130 origin; significantly less often they are formed out of river waters or are of a mixed type
131 (Tolstikhin, 1974).

132

133 **3. Materials and methods**

134 **3.1 The database of aufeis based on the Cadastre (1958) and topographic maps**

135 The inventory map (scale 1:2 000 000) and the Cadastre of aufeis of the North-East of the
136 USSR (Simakov, Shilnikovskaya, 1958), hereinafter referred to as the Cadastral Map and the
137 Cadastre, became the first summarizing quantitative work on aufeis within the territory. The
138 effort was carried out in the framework of the Central complex thematic expedition of the North-
139 East Geological Survey of the USSR.

140 The Cadastre contains data on 7 448 aufeis of different size and over 2 000 boolgunyakhs
141 (frost mounds). Of the total number of aufeis, 7 006 are plotted based on air-photo interpretation
142 data, and another 442 on geological reports from field data. It should be noted that aufeis were
143 identified based on geomorphologic features, meaning that in some cases only the areas or river
144 valleys with aufeis were identified but not aufeis themselves.

145 In the Cadastre (1958) and our digitalization, the following characteristics of the aufeis are
146 presented: location (the name of the river, the distance from the mouth or source), size
147 (maximum length, average width, and area) and the dates of ice recording in aerial images
148 (ranging from 08.06.1944 to 27.09.1945). Areas of the aufeis were evaluated via planimetry.

149 Only very large aufeis ($> 3.3 \text{ km}^2$) were plotted on the Cadastral Map (1958), while the
150 others are shown as point locations. Each aufeis on the Cadastral Map (1958) has its
151 corresponding number, whose identifier and corresponding information can be found in the
152 Cadastre (1958). As noted by Simakov and Shilnikovskaya (1958), some very small aufeis
153 ($< 0.01 \text{ km}^2$) could have been missed due to their indecipherability on aerial images, or they
154 might have already melted by the time of the aerial photography. The example of the Cadastral
155 Map's sheet (1958) for the Indigirka River upper reaches is presented in fig. 2.

156 Here, we developed the GIS database of aufeis in the Indigirka River basin up to the cross-
157 section at the Vorontsovo gauging station based on the Cadastre (1958) and topographic maps.
158 Our compilation contains data on 896 aufeis. The aufeis are presented as point objects in our
159 database. The areas are specified for only 808 aufeis. The total area of all the aufeis with
160 specified area accounts for 2063.6 km^2 and the areas of individual aufeis vary from 0.01 to 82
161 km^2 .

162 In the Cadastre, the dates of ice recording for 592 aufeis (66%) are presented, based on
163 aerial images within the study area. The average seasonal date of recording is August 2, ranging
164 from June 8 to September, 27. The dates of ice recording for the remaining 34% of the aufeis
165 were not described, meaning that aufeis detection could be carried out based not on the visible
166 ice presence at the aerial images but on geomorphological features of river valleys. Therefore,
167 the Cadastre might contain data on old aufeis glades, where the aufeis themselves were absent.

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

178 The locations of the remaining aufeis were determined with the positioned map of the
179 Cadastre. Additionally, 11 aufeis were found, which were absent in the Cadastre, but present in
180 the topographic maps. Aufeis areas were estimated by digitalization of the maps. Areas of the
181 remaining aufeis were estimated with the Cadastre. It was not possible to estimate the area of 88
182 aufeis, as they were not drawn on the topographic maps and only their location, but not area, was
183 stated in the Cadastre.

184 Table 1 contains the structure of the GIS dataset of aufeis according to the Cadastre.

185 3.2 Identification of aufeis based on Landsat data

186 Aufeis location and area are relatively easy to determine using Landsat and/or Sentinel-2
187 images, received immediately after snow cover melting. Snow and ice are known to be
188 characterized by relatively high reflectance in the visible and near infrared spectral bands and its
189 significant decrease in mid infrared band. Normalized Difference Snow Index (NDSI) is based
190 on this pattern and is calculated according to the formula (Hall et al., 1995):

$$191 \quad NDSI = (GREEN - SWIR1) / (GREEN + SWIR1),$$

192 where SWIR1 is reflectance in mid infra-red band ($1.56 - 1.66 \mu\text{m}$ for the Landsat-8 images),
193 and GREEN is reflectance in the green band ($0.525 - 0.6 \mu\text{m}$ for the Landsat-8 images).
194 Following Hall et al. (1995), the threshold value for snow and ice is set at 0.4. Apart from using
195 NDSI, other indices have been suggested to detect aufeis by Landsat images (but not used here).
196 These are Normalized Difference Glacier Index (NDGI) and Maximum Difference Ice Index
197 (MDII). Their advantages and disadvantages are discussed by Morse and Wolfe (2015).

198 Landsat-based detection of aufeis required some additional data to exclude other surface
199 types with similar spectral characteristics, such as snow-covered areas, turbid water, etc. It is

200 problematic to separate floodplain lakes from aufeis by late-spring satellite images, because
201 many of these lakes are still ice-covered in May-June. Morse and Wolfe (2015) recommended
202 creating a mask of water surface by mid-summer images (when all water bodies are already not
203 covered by ice), to exclude them from further analysis.

204 Aufeis detection in the Indigirka River basin was carried out based on the Landsat-8 OLI
205 satellite images, 2013-2017, downloaded from the United States Geological Survey web-service
206 (<https://earthexplorer.usgs.gov>). We used Landsat 8 collection 1 level-one terrain-corrected
207 product (L1T) with radiometric and geometric corrections. In total, 33 images completely
208 covering the Indigirka river basin were processed. We selected late-spring images (between 15
209 May and 18 June), to detect the maximum possible number of aufeis, since in June they melt
210 intensively. There was between 1-20% of cloudiness in some images.

211 Preprocessing of the images was performed with the use of Semi-Automatic Classification
212 Plugin module (QGIS 2.18). It includes the calculation of surface reflectance and atmospheric
213 correction by Dark Object Subtraction (DOS1) image-based algorithm, described by (Chavez,
214 1996).

215 The Aufeis detection algorithm was realized in ArcGIS with the help of the ModelBuilder
216 application. Apart from the Landsat images, the digital terrain model (DTM) GMTED2010
217 (Danielson and Gesch, 2011) with a spatial resolution of 250 m was used to build a network of
218 thalwegs within the study basin. This is essential for semi-automated separation of the aufeis
219 from snow-covered areas in late-spring Landsat images. Indeed, almost all aufeis are located
220 either at streams or thalwegs, or in immediate proximity to them. On the contrary, the snow
221 cover in late spring mainly remains on mountain ridges and other elevated locations, i.e.
222 relatively far from thalwegs. Based on the preliminary analysis of aufeis location in relation to
223 the created network of thalwegs, we found that a 1.5 km wide buffer zone around the thalwegs
224 covers almost all aufeis. So, snow and ice covered areas, which are located outside this buffer,
225 are excluded from further analysis.

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

- 227 • Detection of snow-ice bodies with the NDSI threshold of 0.4.
- 228 • Creation of a water mask with threshold values of the Normalized Difference Water
229 Index (NDWI) (taken equal to 0.3), and reflectance in the near-infrared band (taken equal
230 to 0.04).
- 231 • Extraction of the detected snow-ice bodies by the buffer zone around thalwegs (1.5 km
232 wide).
- 233 • Conversion to vector format, area calculation and removal of objects smaller than 5
234 Landsat pixels (0.45 ha).

235 The suggested algorithm allows successful aufeis detection if an image is predominantly
236 snow-free. At the end of May/early June, many aufeis in mountain regions are still covered by
237 snow. Their detection required later images, obtained in mid-June.

238 Morse and Wolfe (2015) suggested a new spectral index MDII for automatically
239 distinguishing snow bodies from ice ones. However, here some of the high elevation aufeis were
240 partially covered with snow at the image acquisition time. Instead of automatic processing, the
241 outlining of high elevation aufeis was conducted manually when snow cover was present, with
242 separation of aufeis from adjacent snow covered areas.

243 Further, during melt season, the aufeis often divide into several neighboring areas. When
244 assessing the number of aufeis with satellite data, it is therefore necessary to aggregate the areas
245 into one aufeis, if they are located at a distance <150 m (or five Landsat pixels) from each other,
246 and within one aufeis glade.

247 As a result of semi-automated processing of Landsat images, aufeis with a total area of 1
248 253.9 km² were detected. During the subsequent comparison with the Cadastre data (see section
249 3.3 for more details), over 100 aufeis, with a total area of 33.5 km², were delineated manually.
250 The gaps were mainly due to the presence of snow cover and/or cloud coverage in the images.
251 To reduce the number of gaps, two to three images of the same territory were used. The total

number of aufeis, identified with the Landsat images in the Indigirka River basin, was 1 213 and their total area 1 287.4 km². Therefore, an omission error of automatic aufeis detection can be estimated as 2.7% of their total area.

The structure of the GIS dataset of aufeis according to Landsat images is presented in Table 2.

3.3. Cross reference between historical and satellite-based aufeis data collection

Cross-verification of aufeis data collections by the Cadastre (1958) and satellite imagery was performed in two steps. At the first step, we found the closest aufeis in the Landsat-derived dataset for each aufeis from the Cadastre data if the distance between them was less than 5000 m. The determination of search radius was based on a preliminary analysis of the aufeis locations by the Cadastre in relation to Landsat-based dataset. As a result, the cross index (identifier of the closest aufeis in the Landsat-derived dataset) and minimum distance (m) to the closest aufeis were determined for aufeis from the Cadastre. For Landsat-based dataset, the cross index is the key field for the reference to the dataset from the Cadastre.

At the second step, a full manual verification was performed to find the mistakenly interrelated aufeis. For example, if the closest aufeis from the Cadastre and from the Landsat-based dataset were at a distance of less than 5000 m, but in different thalwegs, they were considered as different (unrelated) aufeis.

In total, 260 aufeis from the Cadastre were not verified by Landsat images. For them, the NoData value (−9999) was set in the Cross Index and Distance fields of attributive table (see Table 1 with the structure of GIS dataset from Cadastre).

4. Results

4.1 Comparison of the historical and modern data collection

The results of the comparison are presented in Table 3. In total, 634 aufeis from the Cadastre were found by 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 Cadastre. But 262 aufeis from the Cadastre were not detected by 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 km² (fig. 3-a). It is likely that since the mid-20th century, when the field observations were conducted and the Cadastre of aufeis was compiled, some aufeis could have disappeared.

A little over half of the aufeis detected by Landsat images are included in the Cadastre: a total of 602 aufeis detected (the total area of 250.4 km²) are not included in the Cadastre (fig. 3-b). Such a significant difference can be caused by the following reasons:

1. In some cases a single aufeis, according to the Cadastre, corresponds with two or more aufeis by satellite image;

2. Aufeis are characterized by significant interannual variability, 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 Cadastre (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 were reported in the Cadastre (1958) and this corresponds to the maximum aufeis area during one or several seasons. With the satellite data, the areas of the aufeis themselves were assessed and when mid-June images were used, the aufeis area was significantly smaller than the typical annual maximum.

Aufeis area distribution according to the Cadaster and satellite data is shown as Lorenz curves (fig. 4). In both cases, the shape of the curves signifies a high degree of irregularity which

302 is similar: 10% of the largest aufeis make up 61 and 57% of their total area according to the
303 Landsat and the Cadastre data, respectively.

304 The cross-verification of the Cadastre and satellite data show that almost 60% of aufeis
305 that are unconfirmed in the Landsat imagery and that are therefore only present in the Cadastre,
306 have an individual aufeis area less than 0.25 km² (Fig. 5-a). The confirmed aufeis account for
307 about 20% of the area stated in the Cadastre. Thus, it was mainly small aufeis that were not
308 confirmed in the Landsat images. Conversely, Fig. 5-b shows that almost 60% of the aufeis
309 detected in the Landsat images but not listed in the Cadastre have an area each of less than 0.25
310 km².

311 **4.2. Aufeis distribution by elevation**

312 In general, aufeis distributions by elevation as assessed with the Cadastre and Landsat data
313 are quite similar, although there are some differences that are elevation-specific (fig. 6). Most
314 aufeis are located in the elevation band of 1 000 – 1 200 m. At lower elevations (up to 800 m)
315 the number of aufeis according to Landsat data is higher than stated in the Cadastre. At the
316 elevations of 1 400-2 000 m, more aufeis are identified in the Cadastre data than by the satellite
317 images. This can be explained by the fact that many aufeis located at high altitudes often have a
318 small area, so they could have been missed during the analysis of the satellite data. Further, they
319 could have been covered with snow at the image acquisition time, which would increase the
320 possibility of them being missed.

321 The elevation band of 200-300 m is characterized by the location of large aufeis. Though
322 less than 2.5% and 5.0% of aufeis by the Cadastre and Landsat images are situated here, they
323 represent about 11 and 13% of aufeis area from the datasets respectively (fig. 7).

324

325 **4.3 Aufeis distribution by river basins**

326 In the Indigirka River basin, there are several zones with a high density of aufeis: in the
327 southern part (the Suntar and Kuidusun Rivers basins), as well as in the central part (Chersky
328 Range slopes) (fig. 8). The largest aufeis identified with satellite images are located in the
329 Syuryuktyakh River basin on the north-east slopes of the Chersky Range. Meanwhile, aufeis are
330 almost absent in the northernmost (lowland) part of the Indigirka basin.

331 We analyzed the aufeis coverage for six river basins with available streamflow data. The
332 headwater part of the Indigirka River, with the gauge near the Yurty village (area 51 100 km²), is
333 the basin with the largest aufeis coverage (Table 4). Correlation between average elevation of the
334 basins and their aufeis coverage (expressed as a percentage) is statistically significant. Among 6
335 basins, the Spearman rank correlation coefficients between the basin average elevation and
336 aufeis percentage are 0.71 and 0.77 by the Cadastre and satellite data, respectively.

337 **4.4 Aufeis area interannual variability**

338 The assessment of aufeis area interannual variability was conducted in two areas: for the
339 Bolshaya Momskaya aufeis, which is located in the Moma River channel (area in the Cadastre is
340 82 km²), and for a group of large aufeis (total area in the Cadastre is 287.8 km²) in the
341 Syuryuktyakh River basin, which is the left-bank tributary of the Indigirka River.

342 Cloudless images from Landsat-5 (TM), Landsat 7 (ETM+) and Landsat-8 (OLI) were
343 used with the acquisition dates between May 1 and June 30. In the USGS archives, there are no
344 Landsat-5 images for the study territory for the 1984-2007 period. This limits the duration of
345 satellite observations on aufeis to the period since 1999 (when the Landsat-7 satellite was
346 launched). Also, the clouds complicate the acquisition of representative data. The list of the
347 acquisition dates and assessed aufeis area values are presented in Table. 5.

348 Both areas are located at low elevations (Bolshaya Momskaya 430 to 500 m and
349 Syuryuktyakh 200 to 500 m), which contributes to the relatively early and intensive aufeis melt
350 in spring. The aufeis reach their maximum area by the beginning of May. Using the available

351 satellite images it is impossible to make a reliable conclusion on aufeis area increase or decline,
352 because the acquisition dates vary significantly from year to year. However, it is possible to
353 make some conclusions based on the available data:

354 1. In 2002-2017 the Bolshaya Momskaya aufeis did not reach the maximum area stated in
355 the Cadastre (82 km²), even though the satellite image was acquired during the first week of May
356 (2005) when aufeis melting had not yet started. Comparing two images, taken in similar
357 conditions (08.05.2005 and 15.05.2013), it was found that aufeis area in 2013 was smaller by
358 18.1 km² than in 2005. Accordingly, the Bolshaya Momskaya aufeis may have seen a decreasing
359 trend over time in its maximum coverage.

360 2. The area of the largest aufeis in the Syuryuktyakh River basin in May 2014 was 78.0
361 km², which is 8 km² larger than stated in the Cadastre. One may note also that the maximum
362 aufeis areas in the Syuryuktyakh River basin were detected by the images received at the end of
363 the period (2014-2017), including mid-June (18.06.2015). Therefore, it can be suggested that the
364 aufeis areas within Syuryuktyakh River basin have not decreased since 2002.

365

366 **5. Discussion**

367 The most important uncertainty in the obtained results relates to our ability to draw a
368 conclusion on the long-term trend of total aufeis area comparing the historical and satellite-
369 derived datasets. The total area of aufeis estimated by Landsat images is 38% less than according
370 to the Cadastre. Is it possible to confirm that such a significant reduction in the aufeis area really
371 occurred? Considering this issue, it is important to emphasize some limitations of the
372 methodology and the created datasets.

373 The main limitation of the historical aufeis dataset is that the Cadastre provides an area of
374 aufeis glades, but not the aufeis themselves. Simakov and Shilnikovskaya (1958) noted that the
375 areas of aufeis glades match the average annual maximum of the ice-covered area. Alekseev
376 (2005) states that the assessment of the stages and patterns of the development of aufeis glades
377 based on the analysis of their landscape and geomorphological features is difficult due to the lack
378 of research on temporal aspects of mutual transitions of landscape facies and their factorial
379 dependencies. However, studying the aufeis landscapes in the central part of Eastern Sayan
380 Mountains, Alekseev (2005) assumes that the vegetation community which is a typical indicator
381 of aufeis development may persist for 200-300 years after the beginning of aufeis processes
382 attenuation.

383 The satellite-derived assessment of the aufeis area has the following main source of
384 uncertainty. It is often impossible to determine the maximum area of aufeis by satellite images,
385 since it is observed at the beginning of snow melt season, when aufeis are still covered with
386 snow. In late spring and beginning of summer, the area of aufeis may already been significantly
387 reduced in comparison with the maximum values, due to melting and mechanical destruction.

388 Maximum intensity of aufeis melt in the studied region is observed in June when spring
389 flood river streams actively erode the aufeis surface. Sokolov (1975) reported the results of the
390 observations at the Anmyngynda aufeis carried out in 1962-1965. This aufeis is located in the
391 upstream area of the Kolyma river basin (723 m a.s.l.) and may be used as being representative
392 of the mountainous part of the studied region. In 1962-1965, the aufeis area changed from 5.1 to
393 6.2 km² with mean maximum area of 5.7 km². Aufeis melt has been observed to begin on
394 average on the 10th of May. During May, the aufeis area decreased by 15% of the total area on
395 average. At the end of June, the remaining area was 34% of the maximum, i.e. during this month
396 more than 50% of the aufeis area has been destroyed. In the period from July to September, the
397 melting slowed down: in July the aufeis decreased by 22%, in August by 8%, in September by
398 3%. The area of aufeis at lower absolute elevations decreases faster at first half of the summer,
399 and in the upstream areas – in the second one (Sokolov, 1975).

400 Some aufeis in the mountainous regions could be missed by satellite images, since they
401 can be covered with snow until the end of June. However, their contribution to the total area is
402 non-significant.

403 Taking into account all the above-described limitations, and also that more than 600
404 aufeis that were missing in the Cadastre were found by Landsat images, we conclude that it is
405 not correct to make a conclusion about long-term trends of aufeis area based on the entire created
406 dataset. Following Pavelsky and Zarnetske (2017), we decided to examine only several of the
407 largest aufeis deposits in order to identify the long-term trend.

408 We selected the 38 largest aufeis with an area ≥ 10 km² according to the Cadastre dataset,
409 confirmed by satellite data. Their total area decreased from 858.1 km² according to the Cadastre
410 to 356.3 km² according to recent Landsat images. Conversely, we also selected the largest aufeis
411 according to satellite data (18 aufeis with satellite-estimated area ≥ 10 km²). Their total area also
412 decreased significantly (from 428.6 km² according to the Cadastre to 343.5 km² according to
413 Landsat images). We also analyzed 8 giant aufeis with areas ≥ 35 km² according to the Cadastre
414 dataset. They all were confirmed by the satellite images; however seven of the eight had a
415 significantly smaller area (from 2 to 21 km²) with the decrease being 2-10 times. Only one giant
416 aufeis in the Syuryuktyakh River basin has the area by Landsat larger than by Cadastre, at 72 and
417 64 km² accordingly. It should be noted that the formation of new (mainly small) aufeis can
418 slightly reduce the rate of the aufeis area decrease.

419 6. Conclusion

421 The research conducted here is the first step of the study aimed at the development of a
422 GIS database of the aufeis of North-East Russia. Historical data of the Cadastre (1958) and
423 topographic maps were used to create a geodatabase of aufeis in the Indigirka River basin (up to
424 the Vorontsovo gauge, with the area of 305 000 km²). It contains historical data on 896 aufeis
425 with total area of 2063.6 km². Aufeis detection was conducted for the 2013-2017 period using
426 Landsat imagery with 1213 aufeis identified having a total area of 1287.4 km². The historical
427 dataset from the Cadastre (1958) and more recent satellite-based dataset were compared and
428 combined in the joint Catalogue of aufeis within the Indigirka River basin, available at the
429 PANGAEA repository (<https://doi.pangaea.de/10.1594/PANGAEA.891036>).

430 Recent total aufeis area is 1.6 times smaller than stated in the Cadastre (1958). The more
431 significant changes occurred to 38 large and giant aufeis (area ≥ 10 km²) with total decrease of
432 area by 501.8 km² (or 66% of the total reduction). Simultaneously, the historical Cadastre
433 archive is lacking data on over 600 aufeis that were identified using satellite images. This
434 suggests that the Cadastre data is incomplete, while there may also have been significant change
435 in aufeis formation conditions in the last half century.

436 The analysis of large and giant aufeis seems to indicate that there has been a significant
437 decrease in aufeis area over the period of last 70 years. Additional analysis of historical aerial
438 photography data could help to clarify the issue of aufeis area decline trend since the middle of
439 the 20th century to the present. One of the further study goals will be to find out the extent to
440 which these changes are climate-derived and to identify their impact on river streamflow.

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443
444

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Table 1 The structure of GIS database of aufeis by Cadastre (1958)

| Field name | Field alias | Description |
|------------|---|--|
| FID | FID | Index number (Object ID) |
| AufDataSrc | Aufeis data source | Aufeis Cadastre data (1958) (for all objects) |
| Auf_area | Aufeis area Cadastre (km ²) | Aufeis area (km ²) from the Cadastre (1958). If the data was missing, the area was calculated by topographic maps (1980) scale 1: 200 000 |
| Auf_index | Aufeis index Cadastre | Index of the aufeis in the Cadastre (1958) (it contains 0 if the aufeis was missing in the Cadastre, but found in the topographic map (1980) scale 1: 200 000) |
| Map_index | Cadastre map index | Index of the Cadastre (1958) map |
| Auf_topo | Aufeis in topo | Presence of the aufeis at topographic map (0 – missing, 1 – present) |
| Auf_in_map | Aufeis in map | Presence of the aufeis in the Cadastre (0 – missing, 1 – present) |
| Toponumber | Topo number | Nomenclature of the topographic map sheet |
| Date | Date | Date of fixing the presence of ice within the aufeis |
| Long | Long | Longitude, degree |
| Lat | Lat | Latitude, degree |
| Elevation | Elevation | Height above sea level (determined by Aster GDEM), m |
| Comment | Comment | Comments (mainly typos in the Cadastre map, or the method of determining aufeis area) |
| CrossIndex | Cross index | Cross index of aufeis derived from Landsat (if aufeis is not in Landsat, the value is missing) |
| Distance_m | Distance (m) | Minimum distance between the aufeis from the Cadastre and the same aufeis from Landsat image (m) |

Table 2 The structure of GIS database of aufeis by Landsat images (2013-2017)

| Field name | Field alias | Description |
|------------|--------------------------------|--|
| FID | FID | Index number (Object ID) |
| AufDataSrc | Aufeis data source | Landsat images (for all objects) |
| WRS2_ID | Landsat WRS2_ID | The Landsat scene identifier in the WRS2 graph of the US Geological Survey (USGS). The first three digits indicate the column number, and last three digits represent the line number. |
| Image_Date | Landsat image date | The date of image |
| Comment | Comment | Additional information, for example, if the aufeis was partly covered by clouds and additional images were used to estimate the area |
| CrossIndex | Cross index | Identifier of aufeis by Landsat images (key field for the reference to the Cadastre data) |
| Auf_Area | Aufeis area (km ²) | Aufeis area by Landsat image, km ² |
| Elevation | Average elevation | Average elevation of aufeis, calculated by Aster GDEM digital elevation model |

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Table 3 Data correlation of aufeis based on the Cadastre (1958) and the Landsat images

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| Data source | Matching aufeis number and area (km ²) | Not confirmed aufeis number and area (km ²) |
|-----------------|--|---|
| Cadastre (1958) | 634 (1905.0) | 262 (158.6) |
| Landsat | 611 (1037.0) | 602 (250.4) |

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562 Table 4 Aufeis area coverage (percentage) in the sub-basins within the Indigirka River watershed
563 by the Cadastre and Landsat data

| River | Area, km ² | Average elevation, m a.s.l. | % aufeis coverage (Cadastre) | % aufeis coverage (Landsat) |
|---|-----------------------|-----------------------------|------------------------------|-----------------------------|
| Suntar River –Sakharinya River mouth | 7680 | 1460 | 0.97 | 0.78 |
| Elgi – 5 km upstream of the 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 |

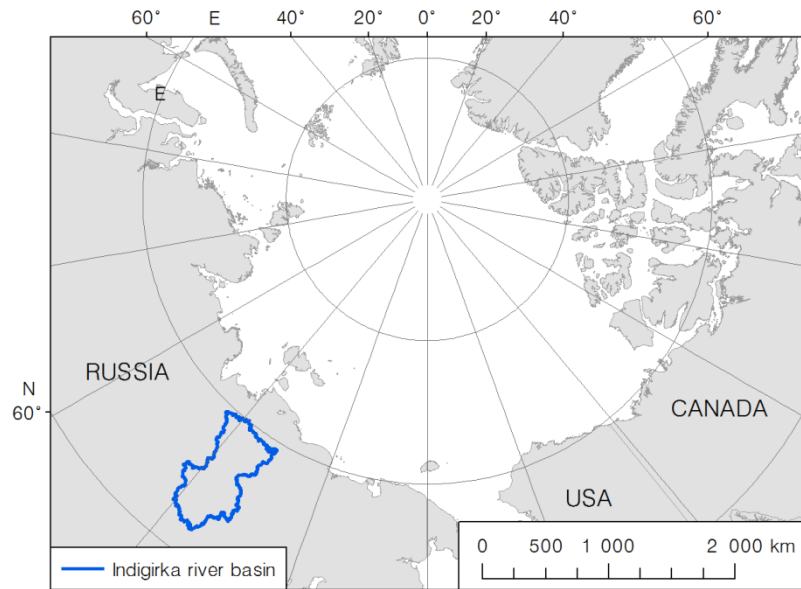
564

565 Table 5 Aufeis area changes, 2001-2017.

| 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 |
| 19.06.2009 | 39.5 | 17.06.2009 | 117.5 |
| 25.05.2011 | 61.7 | 22.06.2011 | 89.5 |
| 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 |

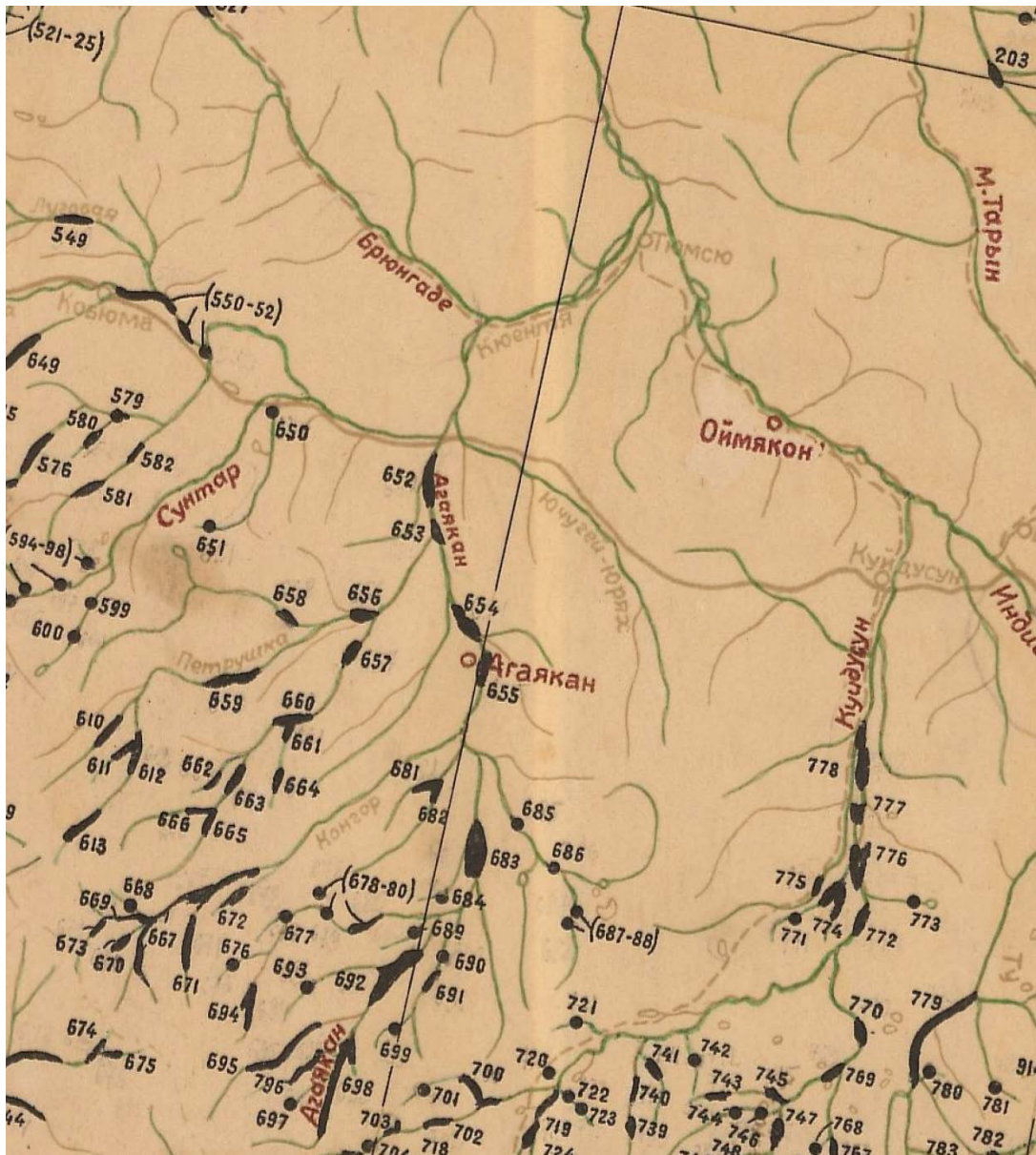
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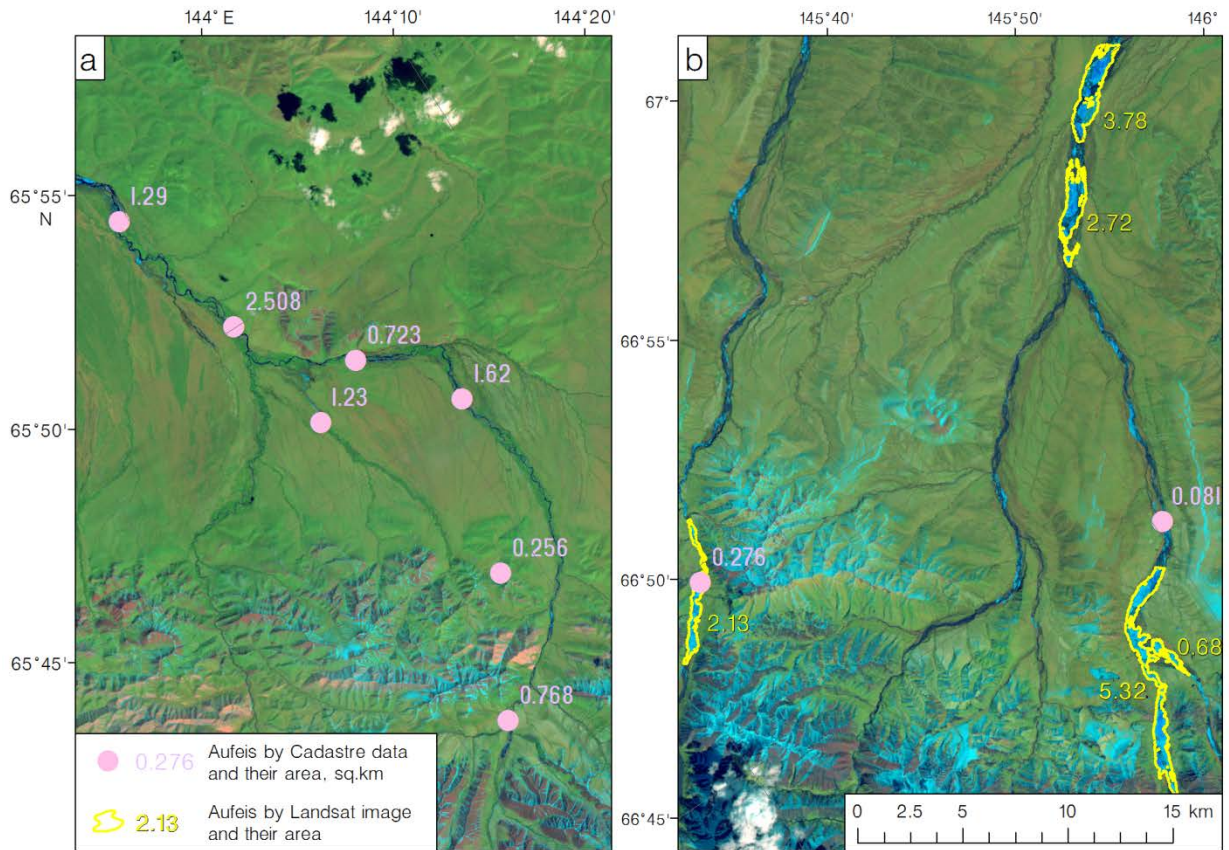
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Fig. 1 Geographical location of the Indigirka river basin



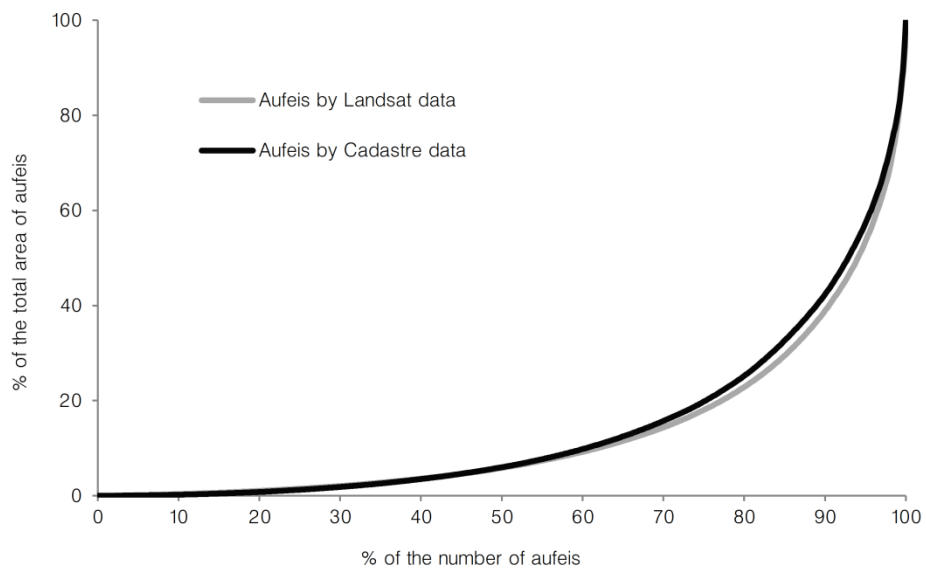
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Fig. 2 Subset of the Cadastral Map of the North-East of the USSR from 1958 (sheet 7, upper reaches of the Indigirka River – the basins of the rivers Suntar, Agayakan and Kuydusun).



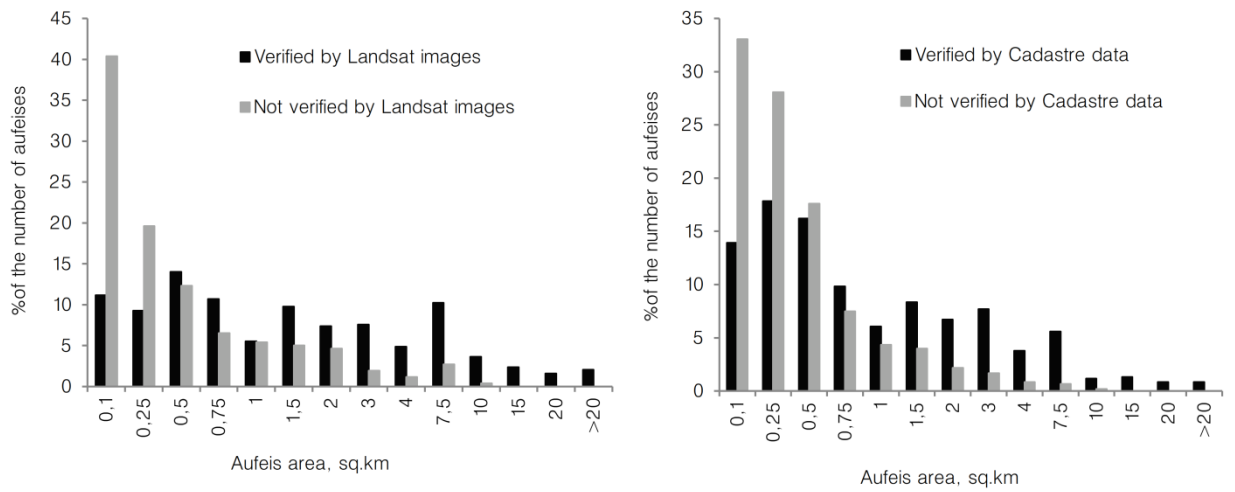
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Fig. 3 Difference between aufeis location according to the Cadastre and satellite data: a) – aufeis are absent in the image but present in the Cadastre (Landsat-8 image of 18.06.2017); b) – aufeis are absent (or their area is understated) in the Cadastre but present in the image (Landsat-8 image of 30.05.2016).



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Fig. 4 Lorenz curves illustrating aufeis area distribution according to the Cadastre and Landsat data



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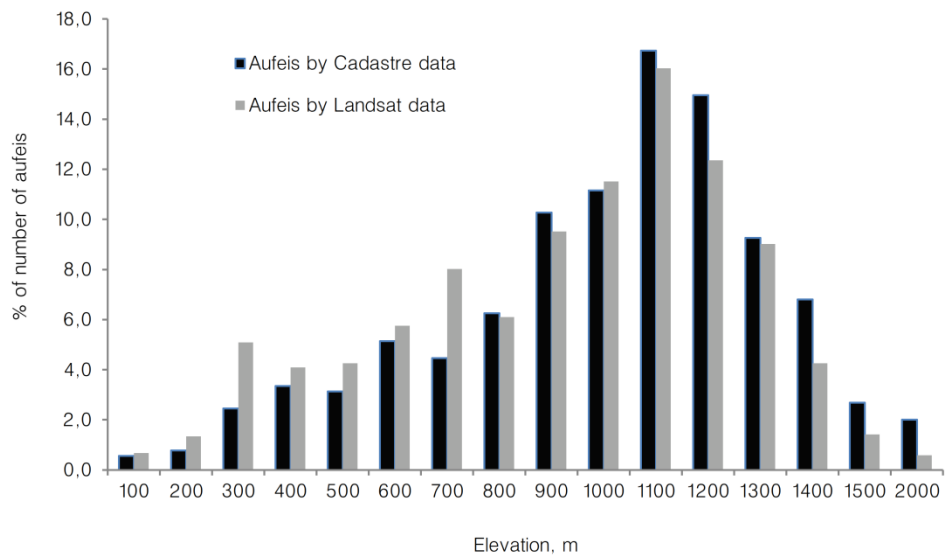
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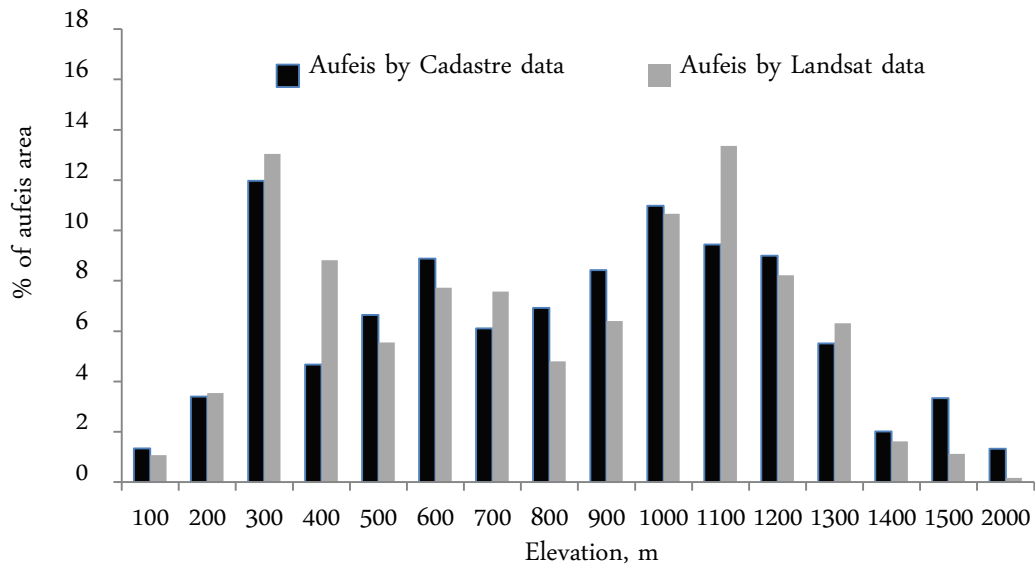
Fig. 5 Aufeis area distribution: a) – according to the Cadastre data, confirmed and not confirmed by Landsat images, b) – according to Landsat images, confirmed and not confirmed by the Cadastre.



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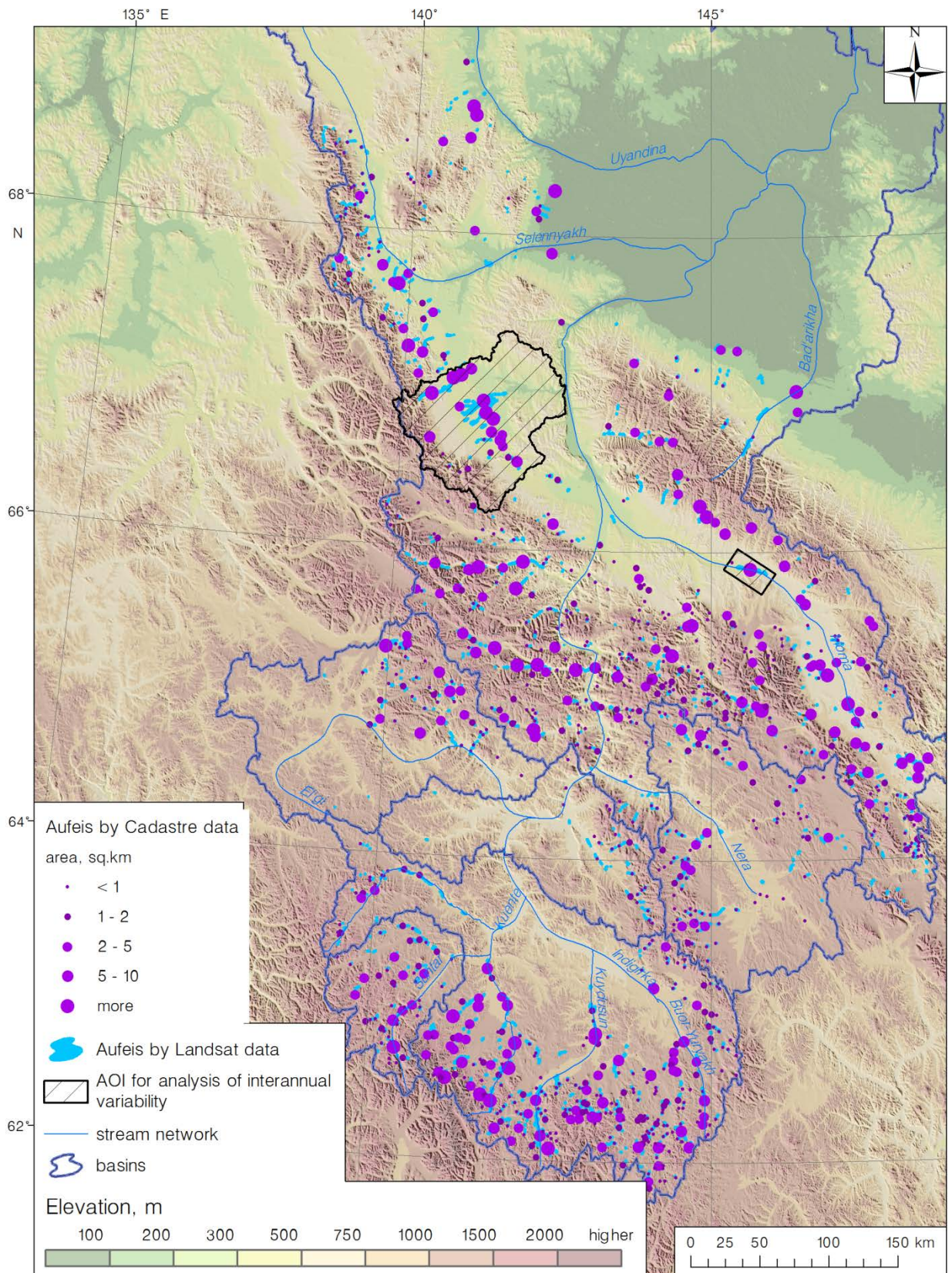
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Fig. 6 Aufeis distribution by elevation within the Indigirka River basin.



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Fig. 7 Aufeis area distribution by elevation within the Indigirka River basin.



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Fig. 8 Aufeis in the Indigirka River basin according to the Cadastre and Landsat images. Black outlines with section lining represent the zones where aufeis area interannual variability was assessed