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The Formation of Aufeis and Its Impact on Infrastructure around Ulaanbaatar, North-Central Mongolia

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The formation of aufeis and its impact on infrastructure around Ulaanbaatar, north-central Mongolia

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Abstract

In this study aufeis features and their formation under natural conditions and in an urban surrounding in north-central Mongolia were investigated. Used methods included field observations, Electrical Resistivity Tomography (ERT) as well as analyses of satellite imagery and meteorological data. Aufeis formation is related to streams, springs, and ground conditions, particularly soil moisture; the formation of both spring aufeis and river aufeis follows a seasonal cycle. The meteorological data from 1969 to 2018 indicate that the mean annual air temperature (MAAT) increased by 2.6 °C, whilst no significant changes were observed for precipitation. Between 1992 and 2018, aufeis areas significantly decreased at all sites, which is likely caused by the air temperature increase. In urban environments, aufeis and its meltwater can damage infrastructure and lead to soil and water pollution. Therefore, urban planning strategies in northern Mongolian settlements should be concerned with aufeis occurrence.

Keywords: aufeis, icing, infrastructure, Mongolia, permafrost

1. Introduction

In 1859, the German-Baltic zoologist Alexander Theodor von MIDDENDORFF (1815-1894) observed ice formations in river valleys, locally called ‘naledj’, during an expedition to Siberia and used the term ‘aufeis’ to describe them. While the international community adopted this German term, ‘icing’ is sometimes used in Canada and Alaska, and aufeis features are known as flood ice, floodplain icing, and ice field (van EVERDINGEN et al. 1998).

Aufeis describes “a sheet-like mass of layered ice formed on the ground surface, or on river or lake ice, by freezing of successive flows of water that may seep from the ground, flow from a spring or emerge from below river ice through fractures” (van EVERDINGEN et al. 1998:52). In the northern hemisphere, aufeis is interpreted as a hydrological phenomenon that is linked to seasonal periglacial processes and has been observed in regions with or without permafrost such as Alaska, Canada, and Siberia (e.g., van EVERDINGEN et al. 1998, POLLARD 2005, YDE et al. 2005, YOSHIKAWA et al. 2007, MORSE et al. 2014, 2015, 2017; MAKARIEVA et al. 2018). It is generally influenced by climate, hydrology, geology, permafrost, and topography (KANE et al. 1981, MORSE et al. 2015). Its seasonal formation has been particularly related to autumn precipitation and winter warming (HALL et al. 1981), while it has negative correlation with snow thickness (CAREY et al. 1973, YOSHIKAWA et al. 1999).

Aufeis usually occurs in valley bottoms and at the foot of slopes, where wet ground conditions result from a high groundwater table. These topographic locations are also the preferred sites for many settlements, but aufeis formation can potentially affect infrastructure. Aufeis-related problems have been reported from China and North America (VINSON et al. 2003, YU et al. 2005, 2007).

Aufeis is a common phenomenon in northern Mongolia. However, little is known about the formation of aufeis and its damaging impacts on infrastructure in Mongolia. While JAMSRAN (1982) described general aufeis observations in Ulaanbaatar, he did not mention any damaging of infrastructure. We are not aware of any other studies on aufeis infrastructure impacts. The purpose of this study is to shed light on these two topics. The results include the presentation of models for the formation of river aufeis and spring aufeis in Mongolia.

1.1. Aufeis formation in Siberia

To get first general understanding of aufeis occurrence and formation, were summarize conditions in Siberia, where streams often flow over permanent frozen ground. Analyses of riverbed boreholes from the upper Amur River revealed that even here, at latitudes of less than 50 °N, permafrost exists (SCHOSTAKOWITSCH 1927). The streams in these permafrost regions generally have low water levels, particularly in winter, and sometimes even freeze out. During the snowmelt season in spring, water levels rise insignificantly, but precipitation during the summer contributes to the highest annual discharge values. The occurrence of aufeis depends on local thermal conditions and valley topography, and typically, the aufeis forms in the same locations from year to year. Aufeis forms during the winter in locations where the water flow is blocked and significantly reduced, so that the water freezes. When the stream was already covered by ice, the blocking of the water might temporarily increase the water pressure and form bulges in the ice cover. The water eventually breaks through the ice cover, and while it flows over the ice towards the riverbanks, it freezes to form aufeis. Depending on the conditions, larger ice fields of significant thickness can develop and even survive in parts during the melt season. Ice fields that extend several square kilometres and are more than 10 m thick are called 'taryn'.

2. Study region

Our two study areas are located 10-50 km east and northeast of Ulaanbaatar, Mongolia's capital, in the lower reaches of the Uliastai and the Baruun Bayan valleys, two smaller tributaries of the Tuul River (fig. 1). Aufeis also exists in locations in the upper Tuul valley and upper reaches of its tributaries, but our study does not cover such locations.

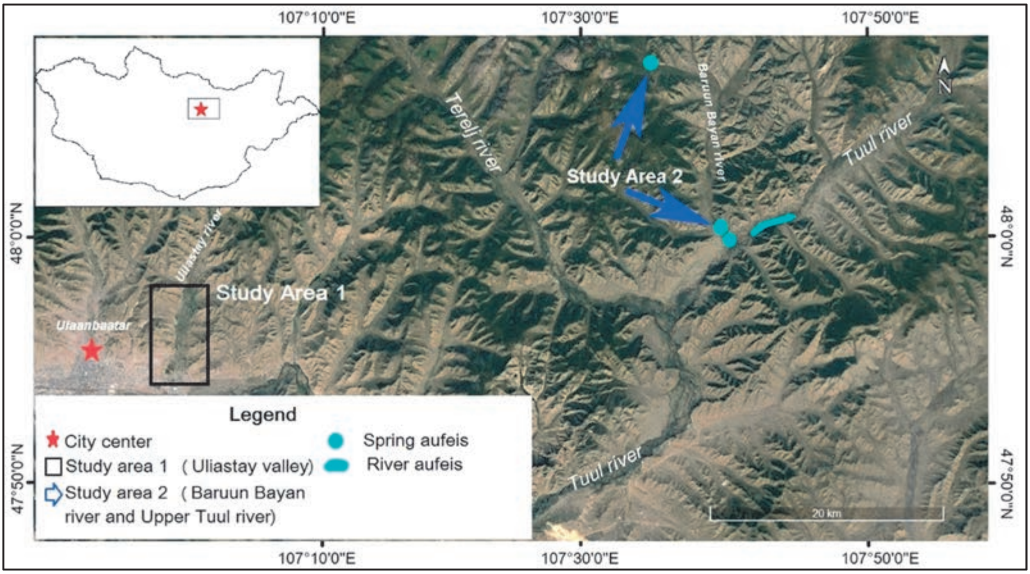

Fig. 1: Study region including two study areas northeast of the capital Ulaanbaatar in central Mongolia.

The study region has an extreme continental climate with harsh winters and dry cool summers. Air temperature and precipitation data from the Ulaanbaatar meteorological station were analysed. From 1969 to 2018, daily air temperatures ranged from -35.9 °C to 30.6 °C - a seasonal air temperature amplitude of around 60 °C - with an average of -0.4 °C and a mean annual air temperature (MAAT) increase of 2.6 °C (fig. 2).

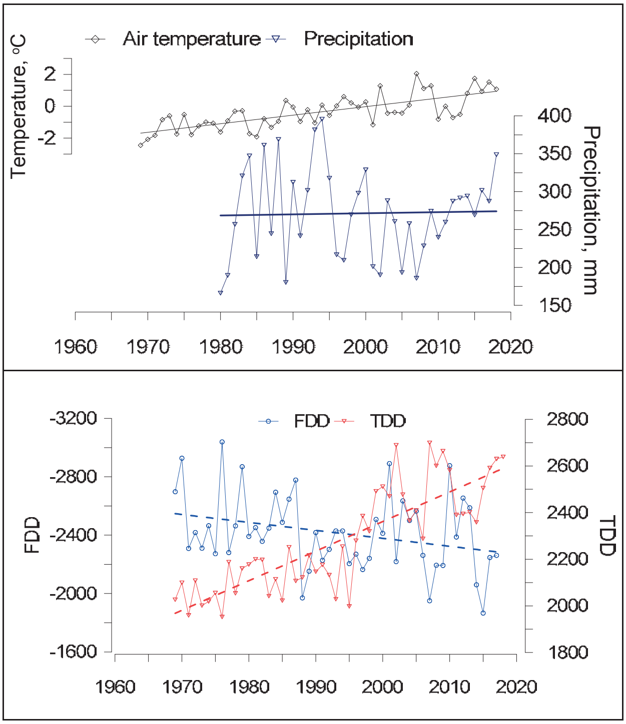

Fig. 2: Climate trends within the study region estimated using data from the Ulaanbaatar meteorological station:

above: air temperature (1969-2018) and precipitation (1980-2018);

below: FDD (Freezing Degree Days) and TDD (Thawing Degree Days) (both 1969-2018).

During the year, temperatures are usually above freezing point from mid-April to mid-October. The freezing degree days (FDD) - the daily degrees below freezing summed over the total number of days the temperature was below freezing - ranged from -3039.5 to -1866.4 and increased by 5.3/year on average. Whilst the thawing degree days (TDD) - the daily degrees above freezing summed over the total number of days the temperature was above freezing - ranged from 1952.5 to 2699.3 and increased at 12.3/year. Between 1980 and 2018, annual precipitation ranged from 166 to 395 mm, with an average of 271 mm. Between 1995 and 2006, precipitation sharply decreased, but then increased continuously in the following years. No significant long-term changes were observed for precipitation. Approximately 90 % of all precipitation occurs between April and September (DASHTSEREN et al. 2014).

In the study region, finer sediments of higher soil moisture occur on the valley floors, whilst slopes are covered with coarser materials with significant amounts of stones and boulders. Several small faults run through the study area, particularly in the lower part of the basin. The study area lies within a transition zone between Siberian Taiga to the North and forest steppes to the South; the generally patchy forest cover overlaps considerably with permafrost areas (DASHTSEREN et al. 2014). Riparian forests are commonly distributed in river bottoms that are sometimes buried under aufeis in winter.

Within the study region were selected two study areas:

- Study Area 1 (SA1) is located at the northeastern border of Ulaanbaatar in the lower part of the Uliastai River sub-basin (fig. 3). The Uliastai River catchment has an area of 705.9 km^2 with elevations of between 1225 and 2773 m asl. It includes several springs, and hummocky ice is a typical cryogenic landform along the river. Within SA1, were studied aufeis features at three sites (U1, U2 and U3) in the lower part of the Uliastai valley. While U1 and U2 represent aufeis formation next to streams in a natural environment, U3 represents aufeis formation and its impact on infrastructure in some distance to a stream within an urban surrounding.

- Study Area 2 (SA2) is located in the Khan Khentii Strictly Protected Area approximately 50 km northeast of Ulaanbaatar in the lower reaches of Bayan Baruun River, a small tributary of the Tuul River (fig. 1). This site represents typical natural conditions for the formation of spring and river aufeis.

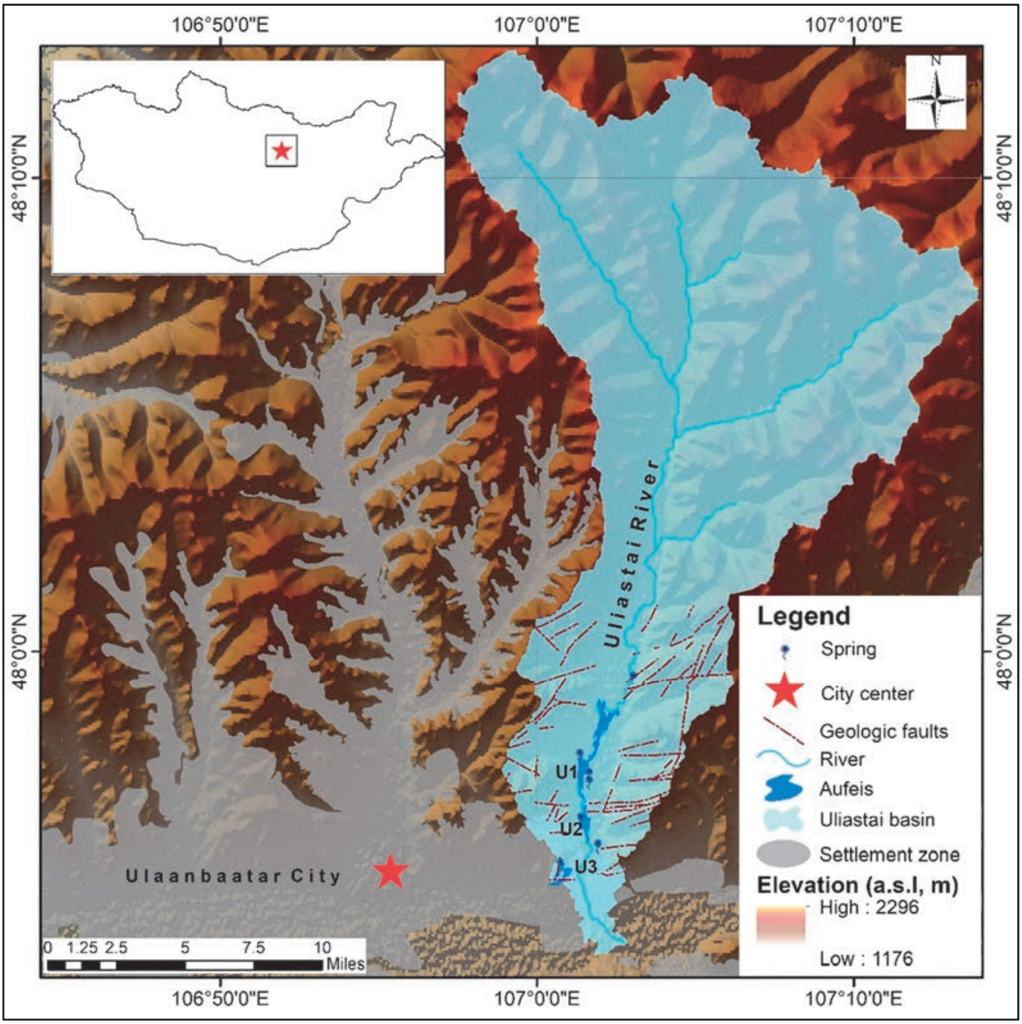

Fig. 3: Study Area 1 (SA1) in the lower Uliastai valley, northeast on Ulaanbaatar. The area includes three observation sites: U1 and U2 in a natural environment, and U3 in an urban surrounding.

In both study areas, permafrost exists under forested north-facing slopes, while on the south-facing slopes seasonal frozen ground occurs (ISHIKAWA et al. 2005, DASHTSEREN et al. 2014). The observations revealed that permafrost is concentrated in the centre of valleys because of higher moisture of the soils.

3. Methods

The used topographic and geological maps at scales 1:100,000 as well as 30 m-resolution Landsat and 15 m-resolution Sentinel-2 satellite imagery (table 1) to map geomorphological and geological landscape features, and to identify aufeis locations; the satellite images were downloaded for free from the Earth Observation System (EOS) platform (https://eos.com/).

Table 1: Satellite imagery used in this study

Date	ID
Landsat Imagery (30 m resolution)	
03/23/1992	LT05_L1TP_131027_19920323_20170123_01_T1
03/26/1993	LT05_L1TP_131027_19930326_20170119_01_T1
03/29/1994	LT05_L1TP_131027_19940329_20170114_01_T1
04/01/1995	LT05_L1TP_131027_19950401_20170109_01_T2
04/03/1996	LT05_L1TP_131027_19960403_20170105_01_T1
03/21/1997	LT05_L1TP_131027_19970321_20161231_01_T1.
03/29/2000	LT05_L1TP_131027_20000329_20161214_01_T1
04/01/2001	LT05_L1TP_131027_20010401_20161211_01_T1
03/11/2002	LE07_L1TP_131027_20020311_20170131_01_T1
09/29/2003	LE07_L1TP_131027_20030929_20170124_01_T1
04/01/2004	LE07_L1TP_131027_20040401_20170121_01_T1
03/19/2005	LE07_L1TP_131027_20050319_20170116_01_T1
04/12/2008	LE07_L1TP_131027_20080412_20161229_01_T1
03/30/2009	LE07_L1TP_131027_20090330_20161222_01_T1
03/06/2011	LE07_L1TP_131027_20110320_20161209_01_T1.
03/06/2012	LE07_L1TP_131027_20120306_20161203_01_T1
03/12/2014	LE07_L1TP_131027_20140312_20161117_01_T1
03/23/2015	LC08_L1TP_131027_20150323_20170411_01_T1
03/25/2016	LC08_L1TP_131027_20160325_20170327_01_T1
03/12/2017	LC08_L1TP_131027_20170312_20170317_01_T1
Sentinel-2 (15 m resolution)	
03/24/2018	S2B_tile_20180324_48UXU_0

Based on several studies (e.g., YOSHIKAWA et al. 2007; MORSE et al. 2014, 2015, 2017; MAKARIEVA et al. 2018) and calculated the normalized difference snow index (NDSI) in mapping the aufeis features:

$$\mathit{NDSI} = (\mathit{Green}-\mathit{SWIR1}) / (\mathit{Green}+\mathit{SWIR1})$$

Since NDSI maps both snow and ice, making difficult to identify aufeis locations, were selected post-snowmelt season satellite images. It is interesting to mention that the snow cover disappears earlier in U3 compared to U1 and U2; probably because of Ulaanbaatar's heat island, effect and it black carbon depositions.

The normalized difference vegetation index (NDVI) to identify any vegetation occurrence in aufeis and aufeis-free locations was calculated:

$$NDVI = (NIR - Red) / (NIR + Red)$$

In late June 2018, we used IRIS Syscal R1 Plus equipment including a switch pro controller and several multi-core cables to carry out an electrical resistivity tomography (ERT) of the ground along two profiles in the study location U3 within SA1. A number of 96 take-out electrodes in both Wenner as well as Wenner-Schlumberger arrays with a spacing of 5 m covering a total length of 485 m were installed in a penetration depth of approximately 85 m.

Fig. 4: Aufeis features formed under natural conditions in the Bayan Barun valley in the upper Tuul River watershed northeast of Ulaanbaatar (photos: M. WALTHER, 2006-2019); above and middle left: ice mounds related to springs; middle rigth and below: river aufeis in riparian forests.

4. Results and interpretation

4.1. Formation of spring aufeis

At SA2 in Bayan Baruun valley, aufeis forms under natural conditions: ice mounds and aufeis developed near springs with perennial water discharge (fig. 4: above and middle left). During the freezing period in autumn and early winter as well as during the thawing period in spring, when freezing still occurs occasionally, frost cracks and other subsurface channels function as 'water pipes' that might get blocked as a result of the freezing. Therefore, the subsurface water in the immediate surrounding of the aufeis cover is under artesic pressure and eventually surfaces. It then spreads out across the ice surface and freezes in the night. With time, this nightly freezing adds to the aufeis sheet in extent and height.

The observed formation of the spring aufeis, for example as ice mounds, in our study region follows a seasonal cycle (fig. 5):

- Summer: gravity springs supply water to their surroundings; they are found either in the lower valley bottoms or at higher topographic locations as part of geomorphologic features such as river terraces or alluvial fans.
- Autumn: subsurface spring water freezes near the surface, particularly around drainages; the ice forces the water into smaller tubes resulting in an increased hydrostatic pressure; the water temperature drops slower than the air temperature; this is a continuous process during most of autumn.
- Winter: the frozen spring water forms ice mounds around the spring because of freezing of hydrostatic water. That is forced through increasingly smaller tubes; cold spring water reaches the surface and freezes immediately as a result of the relative lower air temperature, which leads to a blockage of the spring and forces the water to find a new opening.
- Spring: the spring aufeis thaws at its surface owing to higher air temperatures, and at its boundary owing to higher soil temperatures and developing vegetation; increasing water temperatures in late March and April accelerate the thawing process, and artesic water is pushed towards the surface, preferably the sides of the aufeis cover (fig. 5c).

4.2. Formation of river aufeis

During the visits in autumn and spring at SA2, a thick river aufeis sheet in the floodplain in the upper Tuul River could be observed. The aufeis formed after floodwater had started to freeze at the bottoms of the adjacent meadow and riparian forest (fig. 4: middle right and below). Usually, the Mongolian rivers have their lowest water levels and streamflow in autumn rather than in summer. The floodwater spread out over an already existing river ice cover during the day, and then froze during the night to form typical layered aufeis. The aufeis sheet formed in a riffle-pool sequence that had reduced the streamflow. As a result, water froze first in the pools but continued to flow in the riffle sections. With ongoing freezing, and particularly down freezing towards the riverbed in the downstream positions of the riffles, water was blocked and forced to flood the ice cover.

Comparable to the spring aufeis formation, also the formation of river aufeis area follows a seasonal cycle in our study region (fig. 6):

- Summer: riffle-pool-sequences with a normal runoff peak during the summer season and a significant runoff low in late summer.
- Early autumn: due to lower air temperatures the water surface starts freezing in the pool sections with high water depth, where low runoff speed exists.
- Late Autumn: the water in the pool sections has a total ice cover
- Early Winter: the ice cover of the pool sections reach the low water conditions at the end of the riffle section and water freezes down to the river bottom, what means, that the runoff is totally blocking the runoff. The consequence is, that the water now can only run off on the surface of the ice cover what enlarge the thickness of the ice cover as long as water can flow above the ice cover surface (see fig. 5e). The layered ice can reach a thickness of several meter.

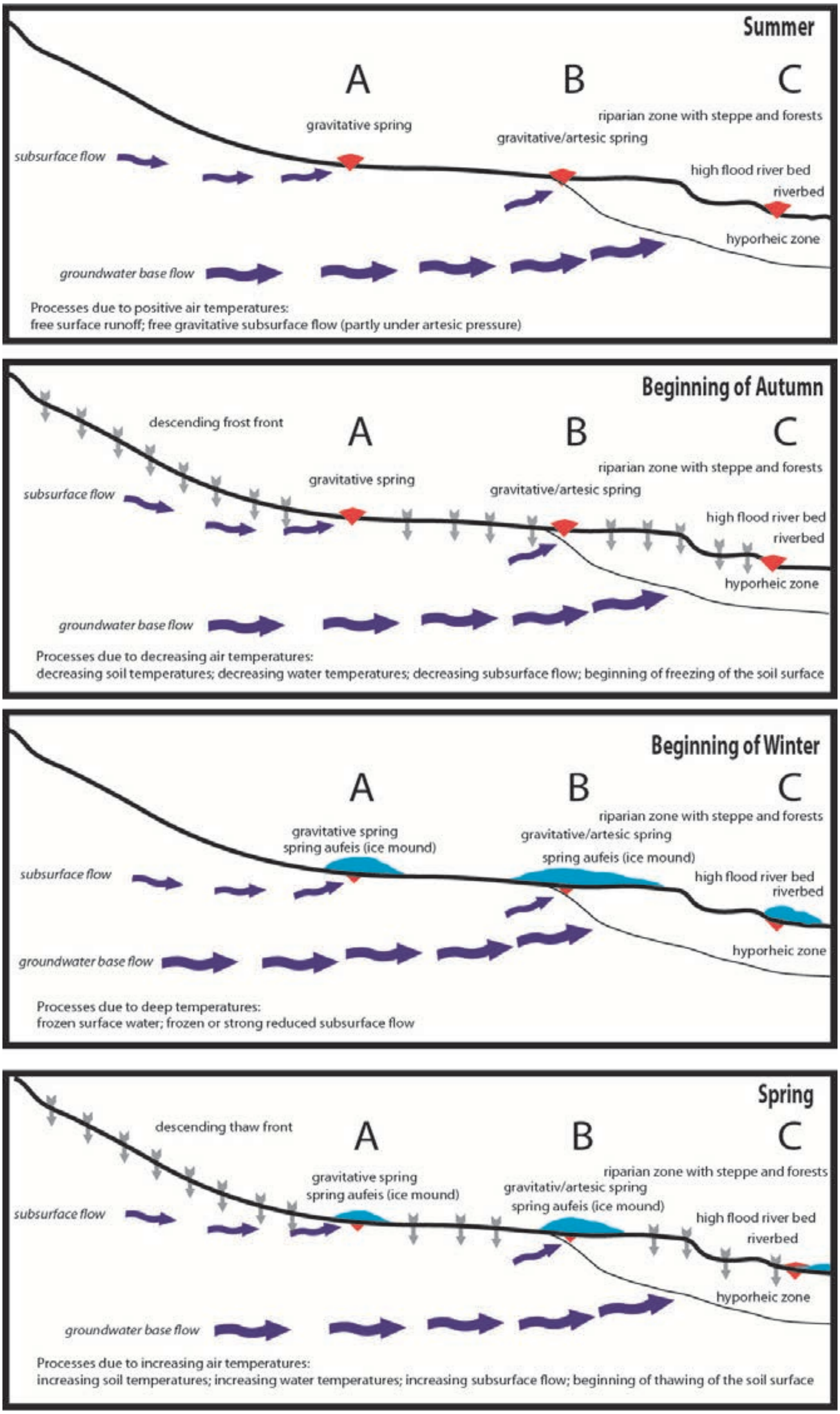

Fig. 5: Hydrological conditions and annual freeze-thaw cycle of spring aufeis (A, B, and C are different possible locations of springs).

- Spring: thawing processes due to increasing air temperatures starts at the ice cover surface and melt water runs off on the ice cover surface. This is accelerating the melt process of the ice cover (see fig 5f).

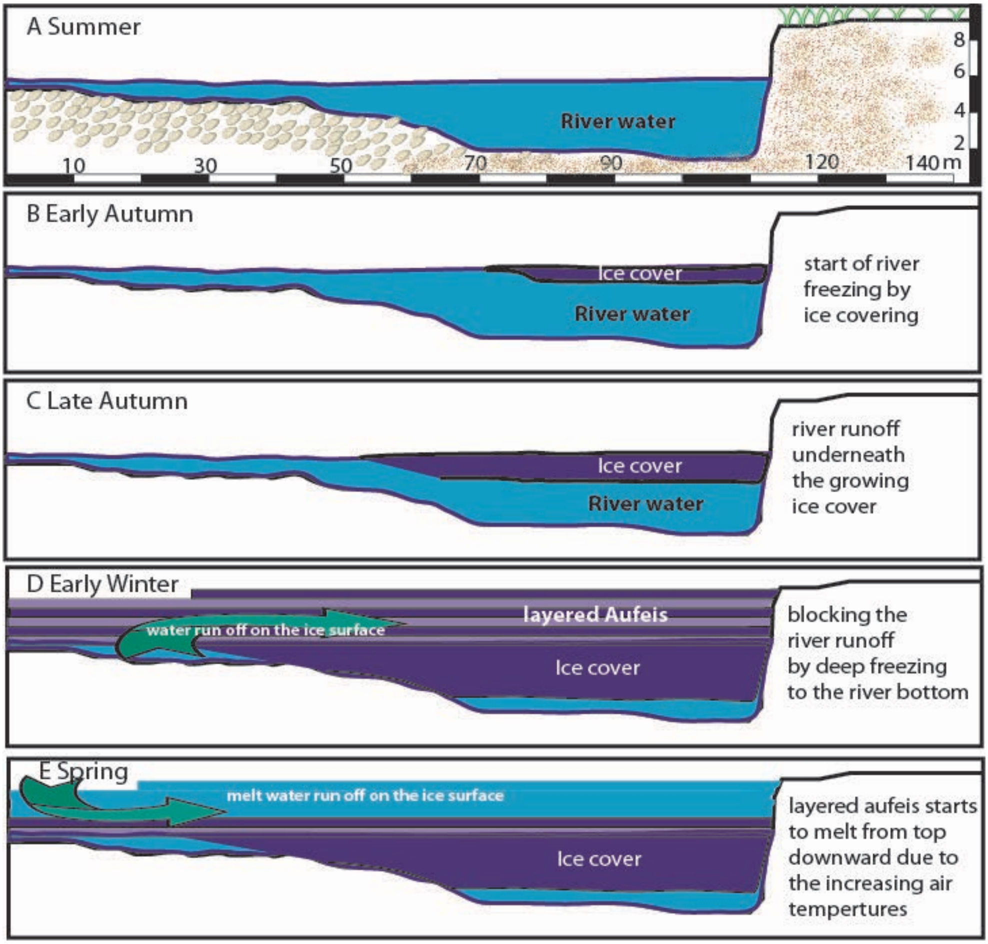

Fig. 6: Formation of river aufeis ('naledj' *sensu stricto*) following a seasonal cycle. Crucial is the time between late autumn (C) and early winter (D), when a developing ice cover starts blocking the river, which results in a smaller channel cross-section that forces water to flow at top the river ice, where it freezes in layers.

4.3. Changes in aufeis area

Between 1992 and 2018, while annual fluctuations occurred, aufeis areas in all three sites U1-3 within SS1 in the Uliastai valley significantly decreased (fig. 7): from 110.0 to 6.4 ha (-94%) at U1, from 38.0 to 6.0 ha (-84%) at U2, and from 55.8 to 22.7 ha (-59.3%) at U3. The aufeis had its largest extents in the mid-1990s, but then significant lost area by the early 2000s. A second period of significant loss was from the early 2000s to the late 2000s/early 2010s. The most significant decrease in aufeis area was noticed at U1, where after 1995 the head portion of the site was permanently ice-free. Since then until 2018, aufeis areas were relatively stable or even slightly increased. In 2018, the aufeis sheets measured 1.2 x 0.4 km or 0.5 km^2 at U1, 1.3 x 0.3 km or 0.4 km^2 at U2, and 0.7 x 0.8 km or 0.6 km^2 at U3.

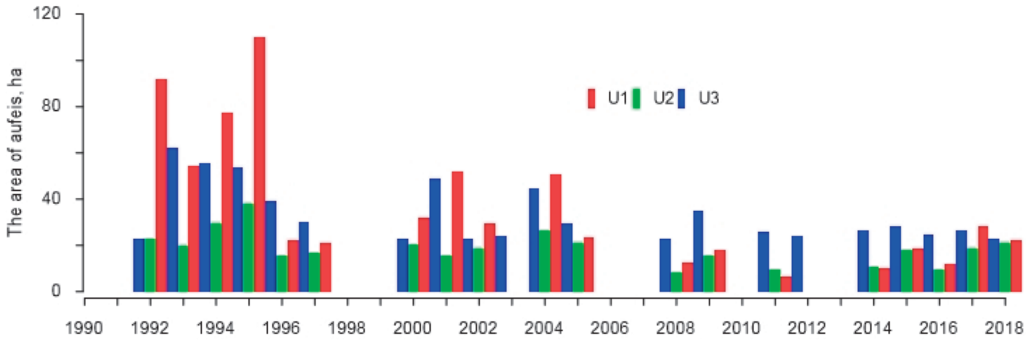

Fig. 7: Annual aufeis areas between 1992 and 2018 at sites U1, U2, and U3 within SS1 in the lower Uliastai valley (gaps result from missing data).

4.4. ERT measurements

In the lower Uliastai valley were carried out ERT measurements along two profiles (ERT1 and ERT2) at U3 within SA1 (fig. 8).

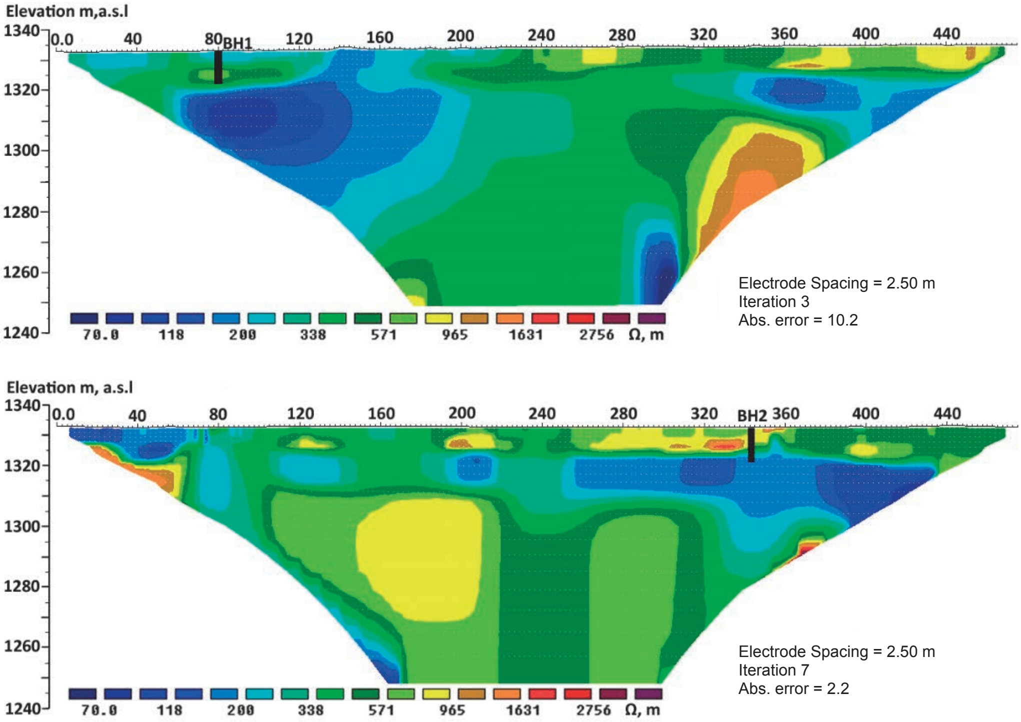

Fig. 8: Electrical resistivity tomography (ERT) profiles at U3 within SA1 in the lower Uliastai valley; above): ERT1 crosses a spring, a fault, and an aufeis area; below: ERT2 runs across a wetland, a stream, and eventually hummocky terrain. Sediment cores were retrieved from two 10 m-deep boreholes (BH1 and BH2; see black markers).

ERT1 crosses a spring and a fault at the beginning of the profile section (0-160 m), and aufeis features in the middle (160-320 m), and end (320-480 m) part of the profile. The resistivity ranges from 60 to 2960 Ωm, and the profile can be divided into ground layers of different water and ice content. Resistivities below 250 Ωm were found here: near the surface in profile section 0-100 m representing water; in 10-20 m depth in profile section 120-140 m representing ground water, and in 10-35 m depth in profile section 180-400 m representing wet ground. Higher resistivities of 250-1000 Ωm were measured in near-surface layers in profile section 100-480 m, which points at the presence of mostly clay and sandy gravels of low moisture content. This was confirmed by results from the analysis of the sediment core from Borehole-2 that reached a depth of 10 m. The highest resistivities of over 1000 Ωm indicating bedrock or permafrost were found in the bottom layers of the entire profile and near the surface of profile section 0-70 m in 5-20 m depth. The low resistivities of less than 250 Ωm in profile section 0-100 m are related to a wet underground connected with the spring and the fault in this section. The aufeis at U3 formed below the spring and, hence, is fed by spring water.

ERT2 profile runs across a wetland, a stream, and eventually, hummocky terrain. Resistivities ranged between 60 and 1700 Ωm, and also ERT2 can be divided into ground layers of different water and ice content. Lowest resistivities of 60-205 Ωm indicating water and wet ground were found here: near the surface in profile section 0-220 m; in 10-55 m in profile section 0-200 m; and in 10-35 m as well as 270-300 m—the bottom of profile—in profile section 320-480 m. Higher resistivities of 250-1000 Ωm occurred at a depth of 6-12 m in profile section 0-120 m and most of the middle part of the profile, and near the surface at the end of the profile. Results from the field survey and the sediment core from Borehole-1 that reached a depth of 10 m revealed that these resistivities correspond to mostly dry clay and sandy gravels as well as patches of permafrost. The highest resistivities of over 1000 Ωm were found in relation to bedrock or permafrost.

5. Aufeis and infrastructure

The multi-temporal satellite analysis revealed that at U3, located within SA1 in an urban surrounding in the lower Uliastai valley, aufeis starts to form in early October and reaches its maximum extent in mid-February. Then it gradually degrades and completely disappears by early May.

With the economic changes that followed the dissolution of the Soviet Union, Mongolia saw a significant rural-to-urban migration. For some regions, like the Mongolian Altai in the country’s west, the out-migration even resulted in a rural exodus (BARCUS & WERNER 2010, KASSYMOVA et al. 2012). One of the top destinations of these migrants is Mongolia’s capital Ulaanbaatar, the country’s by far largest city. While Ulaanbaatar’s population growth was mainly caused by migration from rural areas since at least 1926. This trend significantly outpaced the national’s growth rate in the last three decades. Its population was nearly 600,000 in 1991 and more than doubled to 1.31 million in 2013, representing approximately 46 % of the country’s total population (THE MONGOLIST 2014). This influx of new residents made Ulaanbaatar a densely populated city today: depending on the definition of Ulaanbaatar’s urban area, its population density is between around 280 to 4,400 people/km^2 (THE MONGOLIST 2014). As a result, Ulaanbaatar’s sprawl, mainly in the form of an informal *ger*-suburbia (*ger* = *yurt* = round tent), also reaches into areas, where potential hazards exist such as steep slopes, flooding, or aufeis. While locations with high groundwater tables are suitable for settlements in summer, they are often unsuitable in winter because of aufeis formation inside the *hashaas* (= fenced parcel with houses and/or *gers*), where the aufeis sheet reaches its maximum thickness in January/February (fig. 9). Inside the *hashaas,* the aufeis can damage the fence or even *gers* and buildings; elsewhere it can damage roads, powerline poles, and sewage lines. Another problem is related to the commonly used wastewater pits: during the melting season, aufeis runoff might mix with the sewage and then flush it into local streams or percolate through the ground to reach the groundwater. This contamination of the groundwater with faecal bacteria is a concern for the supply with clean drinking water.

Fig. 9: Aufeis in an urban surrounding in the lower Selbe valley north of Ulaanbaatar (photos: A. DASHTSEREN and Yo. AMARBAYASGALAN, 2018-2019).

6. Conclusions

In north-central Mongolia, spring aufeis and river aufeis are common features, and their formation follows a seasonal cycle. Air temperature has significantly increased since the late 1960s, and this goes hand-in-hand with a significant reduction in aufeis area since the early 1990s. Aufeis can cover valuable pastureland and damage infrastructure. In urban environments its meltwater can mix with sewage and, thus, contribute to pollution of ground and surface water resulting in a serious public health issue. In the light of these problems in a still sprawling Ulaanbaatar, urban planning strategies must consider aufeis as a natural hazard that requires attention, for example in the form of improved sanitation systems.

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