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Changes in aufeis area formed along the Selenge River basin from 2021 to 2025

Undrakhbayar Enkhjargal[1,*], Bilguun Tsogoo[1], Temuujin Khurelbaatar[1], Dashtseren Avirmed[1]

[1]*Institude of Geography and Geoecology, Mongolian Academy of Sciences, Ulaanbaatar15170, Mongolia*

***CORRESPONDING AUTHOR**
Undrakhbayar Enkhjargal
eundrakhbayar@mas.ac.mn
ORCID
0009-0009-6206-0790

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ABSTRACT

Under cold climatic conditions, when the ground surface freezes, pressurized subsurface water emerges through porous soil layers, forming ice accumulations known as aufeis. While aufeis may cause damage to infrastructure and transportation networks in populated areas, they play a crucial role in maintaining ecological balance by enhancing river flows, preserving soil moisture, and serving as freshwater reservoirs. In recent years, the rising average temperatures have led to significant reductions in permafrost and glacial formations, with corresponding decreases in aufeis coverage. This makes detailed investigation of aufeis impacts on both human systems and natural environments particularly important. This study examines spatial and temporal changes in aufeis distribution within the Selenga River basin between 2021 and 2025. The research area encompasses transboundary regions of Mongolia and Russia along the Selenga River basin. Using Sentinel-2 satellite imagery processed through Google Earth Engine, we analyzed aufeis locations and areal extent by calculating spectral indices including the Normalized Difference Snow Index (NDSI) and Normalized Difference Water Index (NDWI). The results of the study indicate that between 2021 and 2025, a total of 35,988 aufeis formations were recorded, covering a cumulative area of 317,976.25 hectares along the Selenga River basin. The year 2021 recorded the highest extent and number of aufeis formations, with 9,053 formations covering an area of 83,123.82 hectares. However, a gradual decrease in both the number and area of aufeis was observed over the subsequent years, reaching a minimum in 2025, when 4,987 formations were recorded over an area of 41,916.61 hectares. Furthermore, our study examined how climatic factors such as mean average air temperature (MAAT) and precipitation have influenced on the changes in both the area and number of aufeis formations.

KEYWORDS

Aufeis, Selenge River, Sentinel-2, NDSI, NDWI

1. INTRODUCTION

During the cold season, when the ground freezes, pressurized water is forced upward to the surface, forming a layered thick ice cover, which is called "aufeis" (khalia in Mongolian). Aufeis are commonly widespread in permafrost regions [1]. In Mongolia, aufeis occur only seasonally, and their formation, development, and processes vary depending on soil, water, and climatic conditions, differing not only by region but also by year. Aufeis typically range in size from 100 to 5000 m², with small to medium-sized aufeis being predominant in the country. The formation process of aufeis usually begins around October-November, becomes active from December to February, and enters a dormant phase by March-April [2].

While aufeis formations can pose substantial challenges to infrastructure, including damage to engineering structures, road networks, and human settlements, they also offer ecological and hydrological benefits. These include maintaining soil moisture during arid spring periods, contributing to the stability of ground moisture into the summer months, enhancing vegetation cover, and supporting sustained river and stream flows [3].

In the Selenga River basin, the average annual air temperature from 1979 to 2016 showed an increasing trend of 1.4°C, or 0.036°C per year [4]. Due to this warming trend, the extent of permafrost and aufeis areas has been noticeably decreasing [5]. Specifically, a 2019 study reported a significant decline in the coverage of aufeis in the Uliastai depression, located northeast of Ulaanbaatar, between 1992 and 2018 [6]. Apart from this study, research on other aufeis affected by climate warming remains limited, making it crucial to expand such studies [7]. Therefore, this article aims to analyze the changes in aufeis areas along the Selenga River basin (2021-2025) using remote sensing methods and examine their temporal variations.

2. RESEARCH METHODS

The study area covers the entire Selenga River basin, including parts of the territories of Russia and Mongolia. To assess the formation and extent of aufeis in the river basin, Sentinel-2 satellite data with a 20-meter resolution was processed using Google Earth Engine.

Satellite imagery of aufeis with 20-30% cloud cover from March to April of each year between 2021 and 2025 was utilized in this study. This specific time frame was selected because data prior to 2021 are limited, and by March to April, the seasonal snow cover on the ground has typically melted, and aufeis formations enter a dormant phase [8].

This study utilized Sentinel-2 Level-2 surface reflectance (SR) images, which provide high geographic accuracy with a 5-day revisit frequency and multispectral imaging capabilities.

To identify the location and area of aufeis from the Sentinel-2 images, NDSI and NDWI were applied. NDWI was specifically used to distinguish water surfaces from aufeis areas.

NDSI is one of the remote sensing methods used to differentiate snow and ice cover on the ground from other land covers, such as soil and rock. Ice and snow absorb short-wave infrared band (SWIR1) while reflecting green band (Green), making it easier to distinguish them from soil and rock. NDSI values typically range between 0 and 1, with values above 0.4 indicating the presence of snow or ice on the surface [9]. NDSI is calculated using the following formula:

$$NDSI = \frac{(Green - SWIR1)}{(Green + SWIR1)} \quad (1)$$

Where NDSI is Normalized Difference Snow Index, Green is the green spectral band and SWIR is the shortwave infrared band.

NDWI is a remote sensing method based on distinguishing aquatic environments from land surfaces and vegetation cover. Water reflects the green spectral band (Green) while absorbing the near-infrared band (NIR), making it easier to differentiate water bodies from soil and vegetation cover. When NDWI values indicate 0.3 or higher, it signifies the presence of water in the given area. In this study, NDWI was employed to examine how the spatial distribution of aufeis correlates with surface water conditions. NDWI is calculated as follows [7]:

$$NDWI = \frac{(Green - NIR)}{(Green + NIR)} \quad (2)$$

Here NDWI is the Normalized Difference Water Index, Green is the green spectral band and NIR is the near-infrared band.

The image processing was performed using ArcGIS software, where a threshold value of 0.4 was applied to the NDSI index to map the spatial distribution and coverage area of aufeis phenomena from 2021 to 2025. During processing, aufeis locations were predominantly identified in geomorphological features including ravines, mountain foothills, valleys, river tributaries, and floodplains [10].

For precise delineation of aufeis areas, the Arc Hydro tool was utilized on 30-meter resolution SRTM (Shuttle Radar Topography Mission) data to compute flow direction, followed by the creation of an 800-meter buffer zone to distinguish aufeis features. Consequently, the total area of aufeis for the period 2021-2025 was compared across the years, and the corresponding changes were quantitatively assessed.

3. RESULTS AND DISCUSSION

According to the results of the study, the total area of aufeis formations along the Selenga River basin between 2021 and 2025 ranged from 41,916.61 to 83,123.82 hectares, while the number of formations varied between 4,916 and 9,053. Among these, the highest number and extent of aufeis were observed in 2021, with 9,053 formations covering an area of 83,123.82 hectares. Conversely, the lowest values were recorded in 2025, with 4,987 aufeis covering 41,916.61 hectares (Figure 1).

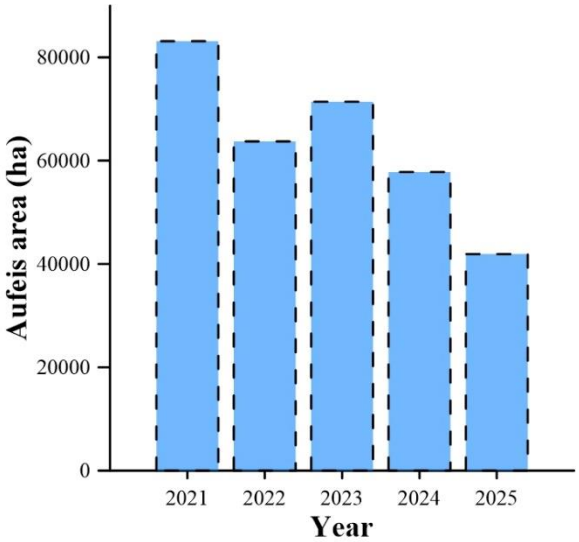

Figure 1. Changes in aufeis area from 2021-2025

Throughout the 2021-2025 period, there was a consistent annual decline in total aufeis area. Notably, in 2023, although the number of aufeis was lower than in the previous year, the total area covered was greater.

Table 1. Aufeis area (hectare) and number along the Selenga River from 2021 to 2025.

Year	Area (ha)	Number of aufeis
2021	83,123.82	9053
2022	63,729.56	8734
2023	71,400.53	8298
2024	57,792.73	4916
2025	41,916.61	4987

In contrast, in 2025, the number of aufeis increased slightly compared to 2024, while the total area decreased (Table 1). These variations may be attributed to interannual differences in precipitation and air temperature, which influence the formation and extent of aufeis [11].

To examine this further, we analyzed the relationship between the number and area of aufeis formations and the annual average air temperature and precipitation for the years 2021 to 2024 (Figure 2). In 2021, when the MAAT was 1.48°C and precipitation was 361.45 mm, both the area and number of aufeis formations were the highest among the observed years (Table 2). In 2022, both parameters declined to 0.65°C and 266.08 mm respectively, resulting in a noticeable decrease in aufeis formation. In 2023, precipitation increased to 350.31 mm while the MAAT dropped to –1.03°C, creating favorable conditions for a larger aufeis area despite a smaller number of formations. The year 2024 recorded the warmest average temperature (1.82°C) over the period, with a moderate level of precipitation (307.88 mm), which likely contributed to a continued decline in aufeis development.

These findings suggest that aufeis formation is closely influenced by interannual climatic variability, with colder and wetter conditions generally supporting greater extent and persistence of aufeis, while warmer and drier years correspond with reduced formation.

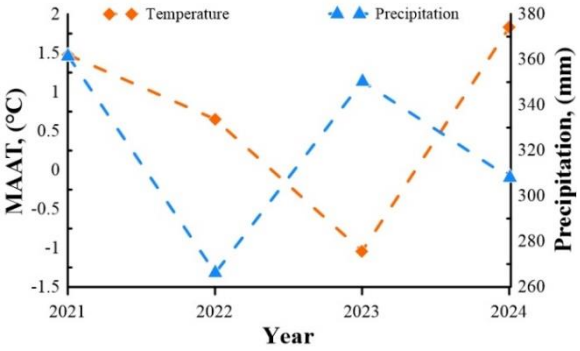

Figure 2. Trend in mean annual air tempertare and precipitation from 2021 to 2024

Table 2. Mean average air temperature and precipitation in the Selenga River basin from 2021 to 2024

Year	Precipitation (mm)	MAAT (°C)
2021	361.45	1.48
2022	266.08	0.65
2023	350.31	-1.03
2024	307.88	1.82

4. CONCLUSION

This study investigated changes in aufeis area along the Selenge River basin between 2021 and 2025. In 2021, a total of 9,053 aufeis formations covering 83,123.82 hectares were recorded. For 2025, this had decreased to 4,987 aufeis formations covering 41,916.61 hectares. Although an overall declining trend was observed, some years exhibited notable variations in both the number and total area of aufeis, likely influenced by differences in annual precipitation and mean annual air temperature.

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