Aufeis in the mountainous areas of the northwestern part of the Selenga River basin

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Abstract. The article presents the results of research on aufeis (icings) in the area where their concentration is maximal for the Selenga River basin. Landsat and Sentinel satellite imagery data were used to map the current location of aufeis in the valleys of permanent watercourses of the transboundary Dzhida River basin. It was found out that up to 3.5 thousand small aufeis with the area from 0.005 to 1 km² are formed in small watersheds of the territory. The total area of aufeis within the considered territory can reach up to 92.1 km², the aufeis coverage is 0.45%. It is revealed that in the total amount, small aufeis prevail, the area of which lies within 0.01 to 0.1 km². In addition, ecosystem and economic aspects of the processes of ice formation on the territory of Russia and neighbouring Mongolia are considered.

1. Introduction

A characteristic feature of the mountainous areas of the northern Selenga River basin is the formation of aufeis in winter in the valleys of small streams. Despite the small areas of ice fields (from 0.01 to 1 km²) compared to, for example, ice in the Northeast of Russia, their total number and density of distribution determine the high aufeis coverage of the territory. According to hydrological studies in the northern (Russian) part of the Selenga basin, there are more than 1,300 permanent watercourses more than 10 km long, with up to 15,000 small aufeis in their valleys annually.

The large area of the northern Selenga basin and the variety of natural conditions explain the different aufeis coverage of the area. The smallest percentage of ice area in relation to the catchment area (0.001-0.05) is observed in the central part of the Selenga middle mountains, in the Uda River basin the aufeis coverage increases to 0.15-0.41% and reaches a maximum in the middle mountain areas in the Dzhida River basin (up to 0.45%). This area, the Dzhida River basin, is of great interest in terms of studying aufeis, as they have relatively large areas here and have a significant impact on the life and economy of the population. Furthermore, the Dzhida River basin is transboundary.

The transboundary basin of the Dzhida River is located on the territory of Russia (18.3 thousand km²) and Mongolia (5.3 thousand km²). The runoff from the territory of the neighbouring country runs through the Zelteriin Gol (Zheltura) River, which is the first-order right tributary of the Dzhida. There are no other tributaries flowing through the territory of Mongolia, therefore, the Zelteriin Gol (Zheltura) determines the transboundary significance of the basin under study.

River and groundwater aufeis are a common phenomenon in the Dzhida basin, both in the Russian and Mongolian territories. This is due to the widespread presence of permafrost in the mountainous terrain and the peculiar climate, which is characterized by significant values of negative accumulated temperature and relatively high precipitation in the warm season [1].
The goal of this work was to map aufeis and identify general patterns of their location within the Dzhida River watershed, as a territory with high aufeis coverage in the northern part of the Selenga basin. In addition to the Russian part of the Dzhida watershed, the Mongolian part was considered separately, which, despite being divided by the state border, is uniform in terms of nature. The objectives of the work included identifying the location of aufeis (ice fields) in the valleys of small rivers of the Dzhida tributaries, counting the number of objects, estimating their current morphometric characteristics, and classifying them according to individual characteristics.

2. Models and Methods

The study of aufeis was based on a well-proven approach based on the use of satellite images with in-depth spectral data analysis. For this purpose, we used Landsat 8 images, which were processed with NDSI. Normalized-Difference Snow Index, or NDSI, is an index, which allows interpretation of snow-ice objects [3]. Its calculation is based on the difference in radiation reflection between the visible green (Green) and shortwave infrared (SWIR) parts of the spectrum [6]. The index can be calculated in different GIS that has a built-in algorithm for raster images (Raster Calculator). The calculation is made with the formula:

\[ \text{NDSI} = \frac{(\text{Green} - \text{SWIR1})}{(\text{Green} + \text{SWIR1})} \]  

For Landsat 8, channels 3 and 6 are used as input data. Images in a wide temporal range are used in the process of ice interpretation. The best and most reliable result is achieved by using images taken by the satellite during the period when the snow cover on the territory has mostly melted. Fields of aufeis in the river valleys during this period are clearly distinguished on the images. The space images taken by the satellite in April were used for the valleys of the Dzhida and the Zelteriin Gol (Zheltura) rivers, and in May – for the mountainous areas of the Dzhida Ridge and Khamar-Daban.

The main difficulty in the interpretation of small aufeis using space images in mountainous areas is the limited possibilities for automation of the process. Snow accumulations in relief depressions, small, often oblong-shaped ice-covered lakes in river floodplains, etc. have similar spectral characteristics as aufeis fields. In order to facilitate the process of highlighting aufeis, a water mask is created in advance, and a buffer zone along the thalwegs is highlighted [4]. Nevertheless, the separation of objects is mainly carried out semi-automatically using the expert method.

3. Results and Discussion

Based on the results of satellite images processing with use of NDSI, the areas of aufeis development on the rivers were established, and a map of aufeis distribution in the transboundary basin of the Dzhida River was drawn (Figure 1). Table 1 presents data separately for the Russian and Mongolian parts of the basin.

Table 1. Main characteristics of aufeis in the transboundary basin of the Dzhida River (by local basins within the states).

| River basin          | Area, km² | Number of aufeis, pcs. | Total area of aufeis, km² | Maximum area of aufeis, km² | Average area of aufeis, km² | Aufeis coverage, % of basin area |
|----------------------|-----------|------------------------|---------------------------|-----------------------------|-----------------------------|---------------------------------|
| Dzhida               | 18,894.3  | 2,383                  | 74.75                     | 1.23                        | 0.03                        | 0.39                            |
| Zelteriin Gol (Zheltura) | 5,057.1  | 1,134                  | 17.43                     | 0.35                        | 0.01                        | 0.34                            |
| Total*               | 23,951.4  | 3,517                  | 92.18                     | 1.23                        | 0.02                        | 0.38                            |

* excluding Dzhargalantyn-Am hollow, where the maps show a drying watercourse, which does not exist for many years and does not flow into the Dzhida.
Figure 1. Map of aufeis distribution in the transboundary basin of the Dzhida River.

The map (Figure 1) shows the current distribution of aufeis on the territory. Comparison of the obtained data with retrospective space images shows that, in general, aufeis are formed annually in the same places. They can migrate along the channel, change their shape and configuration insignificantly, and their sizes are dynamic, which depends on the volume of groundwater reserves, replenished from the surface by precipitation, less often from the depth by rifts.

According to the main morphometric characteristics, the vast majority of the aufeis in the Dzhida basin are classified as very small and small [2]. The number of medium-sized aufeis is 128 (Table 2). Only one large aufeis was identified. It is formed in the Bartoy river valley in the northern part of the basin. This situation is typical for the mountainous areas of the Selenga middle mountains. There is no significant difference in aufeis coverage between Russia and Mongolia because a significant part of the aufeis in the Dzhida basin, including its Mongolian part, are formed in similar natural conditions of small watersheds of the Dzhida Ridge. Only the southern macroslope of the mentioned ridge is characterized by an increase in the total number of aufeis, which is probably related to the larger groundwater reserves of infiltration origin compared to the northern slope, which are replenished by precipitation.

| Category     | Area, km² | Dzhida, pcs | Zelterin Gol (Zheltura), pcs |
|--------------|-----------|-------------|------------------------------|
| Very small   | 0.01      | 776         | 560                          |
| Small        | 0.01 – 0.1| 1,484       | 568                          |
| Medium       | 0.1 – 1   | 122         | 6                            |
| Large        | 1 – 10    | 1           | 0                            |
Although Russia and Mongolia do not differ much in terms of natural conditions of ice formation, the socio-economic importance of this natural phenomenon is different for the neighbouring states. Thus, within the Russian territory, aufeis on rivers pose primarily a threat to the population, while in the Mongolian part, aufeis is primarily a source of water for agriculture.

In the Russian part of the Dzhida basin, agricultural development is limited due to the mountainous terrain and development of permafrost. Arable land and pastures are concentrated in the lower reaches of the Dzhida River. There, where in the conditions of mountainous relief ice is actively developed in winter, pasture cattle breeding is practiced. The available water resources are sufficient for these purposes. But the problems of ensuring safe habitation of people in the areas where active ice formation processes are observed are acute. In this regard, the valley of the Tsakirka River (left first order tributary of the Dzhida) is an example. In the village of Dalakhai in Zakamensky district of the Republic of Buryatia, where the houses are partially located in the floodplain of this river, there is an annual growth of aufeis, which is followed by underflooding of the village. Thus, in February 2020, 32 houses, a kindergarten and a canteen of the local school were flooded in the village. And, since 2016, the area of aufeis has increased every year. Aufeis threatens other settlements as well.

For the Mongolian part of the basin, this problem is not relevant. There are no settlements in the areas of intensive aufeis development in the Zelteriin Gol (Zheltura) basin. There, aufeis play an important role as they determine the runoff of small rivers in the dry spring period, thereby providing water to agriculture. In contrast to the Russian part of the basin, it is more developed here. According to 2020 data, there are 1.7 million sheep alone in the borderline Bulgan aimag (within which most of the Zelteriin Gol basin is located) [5], and water supply is an important component of the sustainable development of local livestock breeding.

4. Conclusion

The work included mapping of aufeis in the transboundary basin of the Dzhida River, revealing general regularities of ice formation processes. The map of the aufeis of the territory shows not only their current location, but also reflects general patterns in the distribution of aufeis within the territory, their multi-year positioning. This is confirmed by the analysis of retrospective space images. It may be noted that similar mountainous areas in the northern, Russian part of the Selenga River basin are characterized by similar features of ice formation. Thus, similar in values of aufeis coverage is observed in the river valleys of the spurs of the Ulan-Bursasy Ridge (the Uda River basin), in the mountains of the eastern part of the Khilok and Chikoy River basins. This similarity also determines the resemblance of the processes of aufeis formation and destruction in these territories, the same share of aufeis flow in the regime of small rivers, and the geoeconomic features of the landscapes of the areas where the aufeis are located.

The study of aufeis also has practical significance. The example of underflood of the settlement by aufeis is not the only one in Buryatia. In the last 2 years, the frequency of emergencies related to aufeis has increased. Thus, in 2021 seven settlements were flooded in the central part of the republic alone. The situation will only worsen in the following years, and it is likely that the large-scale flooding that occurred during high-water years in 1997-1998 will repeat itself.

The presented examples demonstrate how both favourable and unfavourable consequences of intensive aufeis development that impact everyday life and economic development of the population are manifested simultaneously within one transboundary basin. The map of aufeis location created in the course of the study will further complement the comprehensive studies of aufeis formation processes in the Selenga River basin and in the adjacent areas.

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