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Identification of Icings Spreading Patterns in Selenga Middle Mountains by Methods of Geoinformation Analysis

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Abstract: The purpose of this work is to determine the main regularities of icing distribution in the Selenga middle mountains. The objectives of the study included mapping of icings using Landsat imagery and geoinformation analysis of their spatial differentiation. The geoinformation analysis of the distribution of icings in the Selenga mid-mountain depending on various environmental factors (tectonics, relief, permafrost, meteorological indicators) revealed the main regularities of their formation. The relation of the glaciers to different categories according to the main classification features was determined. Icings of the Selenga mid-mountain are divided into 4 size classes (medium, large, very large and giant), 2 main genetic types are identified according to the prevailing sources of supply (groundwater and spring icings), the number of slope and valley icings is determined. The role of relief and snow cover influence on the distribution of icings in the territory was assessed. It has been established that in the current climatic conditions in the Selenga middle mountains 7.7 thousand icings are formed, most of which (70%) belong to groundwater icings. The maximum number of glaciers is observed in areas with a transitional type of permafrost distribution, while valley glaciers prevail in mountainous areas at altitudes from 850 to 1000 m. They are formed along watercourses in intermountain hollows and in the spurs of mountain ranges.

Keywords: icing, permafrost, groundwater, terrain, Selenga mid-mountains, snow cover, tectonic faults, geoinformation analysis.

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1. Introduction

Geoinformation analysis is an effective method for studying the state and dynamics of various landscape components. In this study, we examine icing formations as the research objects. Icings are layered ice masses or crusts on the surface of the ground, ice, or engineering structures formed when periodically discharged natural or man-made water freezes [*Alekseev*, 1976; *Glaciological…*, 1984]. The cold, sharply continental climate of the Selenga mid-mountains leads to seasonal and widespread permafrost, making cryogenic processes, including the formation of icings, quite active. The complex tectonic structure, mountainous terrain, predominance of island permafrost, and the presence of water-saturated gravel deposits in river valleys all contribute to a high number of icings. Depending on the climatic conditions, between 3.3 and 7.7 thousand icings form in this area [*Chernykh et al.*, 2024].

Despite many years of research on icings in Transbaikalia, those in the Selenga mid-mountains are still insufficiently studied. Previous research on icings in the region has focused on areas near the Baikal-Amur Mainline (BAM) [*Chmutov*, 1982; *Markov et al.*, 2016;

Vasekhina, 1980], mountainous regions (Eastern Sayan range, Khamar-Daban, etc.) [*Alekseev*, 1974; 1975; *Glaciological…*, 1984], with some publications on Eastern Transbaikalia [*Alekseev*, 2016; *Shesternev et al.*, 2006; *Zvyagintseva et al.*, 2022].

Therefore, questions about determining the genesis and distribution features of icings, their morphometric characteristics, spatial-temporal dynamics, and the intensity of icing formation in response to global and regional natural and climatic changes are relevant for the Selenga mid-mountains. This study aimed to identify these formation characteristics using geoinformation methods.

2. Materials and Methods

The study area is the Selenga mid-mountains, an orographic region within Western Transbaikalia with a total area of more than 60000 km^2.

Vector polygons of icings (2022) derived from Landsat satellite image decoding, digital elevation models (DEMs) SRTM [*Farr et al.*, 2000] and HydroSHEDS (Void-filled DEM 3s product) [*Lehner et al.*, 2008], tectonic data from [*GIS-packages…*, 2024], refined using 1:200000 scale digital geological maps in SASPlanet software (version 200606), were used as baseline data. Materials from [*Brown et al.*, 2002] were used to assess the role of permafrost in the spatial differentiation of icings, and snow cover data from [*Ecological Atlas…*, 2015].

Icing distribution in the Selenga mid-mountains was mapped based on Landsat-8 satellite imagery (spatial resolution of 30 m) with dates from April 2 to April 22, 2022. Automated image data processing was conducted by analyzing threshold values of the NDSI (Normalized Difference Snow Index) [*Hall et al.*, 1995] according to the technique described in [*Alekseev et al.*, 2022], coupled with visual decoding and manual digitization. The threshold value of NDSI to identify snow and ice surfaces is taken to be equal to 0.4 [*Alekseev et al.*, 2022].

The resulting polygons were compared using vector data on tectonic faults to identify potential sources of icing formation. The distribution of icings based on terrain elevation and slope steepness was analyzed using the void-filled DEM from Hydrological data and maps based on Shuttle Elevation Derivatives at multiple Scales (HydroSHEDS), based on DEM from the Shuttle Radar Topography Mission (SRTM) with a spatial resolution of 90 m (3 arc seconds). HydroSHEDS was chosen because, unlike the original SRTM model, it includes hydrological corrections, improving watershed and talweg delineation accuracy.

The distribution of icings was compared with vector maps of permafrost types and snow cover thickness to clarify their roles. Data processing was conducted in ArcGIS, QGIS, and SASPlanet software.

Results

Figure 1 shows the current distribution of icings in the Selenga mid-mountains compared with permafrost distribution. Currently, in the cold season, 7747 icings form in the Selenga mid-mountains with a total area of 206.4 km^2. According to N. I. Tolstikhin classification [*Tolstikhin*, 1941], this includes 2 giant icings (area more than 1 km^2), 267 large ones (0.1 to 1 km^2), 4827 medium-sized ones (0.01 to 0.1 km^2), and 2651 small ones (less than 0.01 km^2). Smaller icings were not included in mapping based on satellite images, as recommended in [*Alekseev et al.*, 2022].

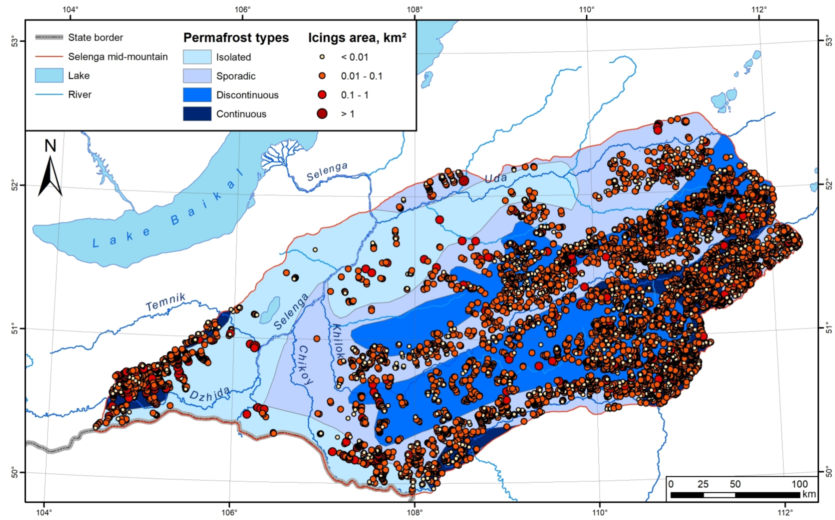


Figure 1. Current distribution of icings in the Selenga mid-mountains (permafrost distribution types by [*Brown et al.*, 2002]).

Figure 2 shows a map of icings located in fault zones. These areas are often associated with hydrogeogenic taliks [*Romanovsky*, 1973], where groundwater from deep aquifers discharges to the surface as non-freezing springs that feed the icings during the cold season.

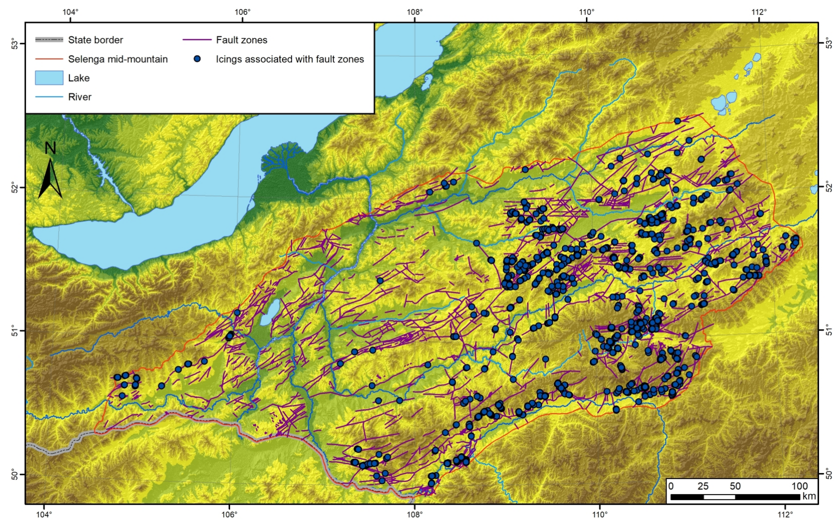
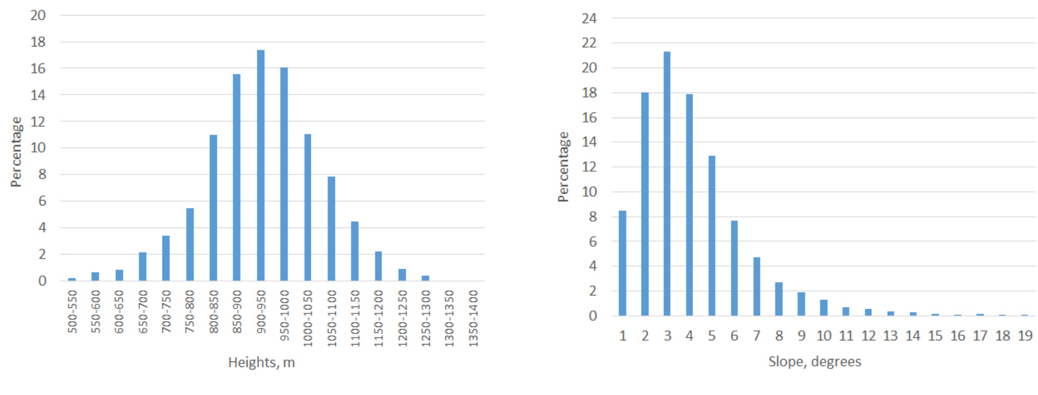


Figure 2. Icings associated with fault zones.

Figure 3a shows the analysis of icing distribution by elevation. The largest number of icings (3400) forms at elevations of 850 to 1000 meters. In the Selenga mid-mountains, these elevations correspond to the foothills of mountain ridges and river valleys in their spurs. Figure 3b presents a diagram of icing distribution by slope steepness.

The largest number of icings (4300) forms in the gently sloping valleys of small rivers. However, there are also a significant number of slope icings forming in mountainous areas with slopes greater than 8°.



(a) **(b)**

Figure 3. Icing distribution in the terrain by elevation (a) and slope steepness (b).

Among meteorological factors influencing icing distribution, air temperature during the cold season and snow cover thickness are the most important. These two characteristics determine the freezing depth of rock, thus affecting groundwater circulation and cryogenic pressure. The results of analyzing the relationship between icing distribution and these parameters are shown in Table 1.

Table 1. Distribution of icings in the Selenga Middle mountains depending on the thickness of the snow cover.

Thickness of the snow cover, cm	Number of icings	Area of the territory, %	Amount of icings, %
<20	1224	49.2	15.7
20–40	5712	45.2	71.5
40–60	776	4.5	10.2
60–80	35	1.1	2.6

Note: snow cover thickness according [*Ecological Atlas…*, 2015].

3. Discussion of Results

In areas where icings have not been studied in detail, identifying general patterns of their formation is relevant. The most important aspects include determining the genesis of icing-forming water, clarifying their size and location in the landscape, and examining how various environmental factors influence their development intensity. Geoinformation analysis methods are well-suited for these purposes, as they enable assessment across large areas. Some data, such as the relationship between icings and fault zones, are challenging to establish without specific field investigations. GIS technologies, albeit with some conditionality, allow for such analysis.

Figure 1 shows that most icings form in mountainous areas with discontinuous or continuous permafrost coverage, where they are notably abundant. In regions with a continuous, thick cryolithozone (such as Northeast Russia), the density of icings per area is considerably lower, although their sizes are larger due to limited groundwater discharge on the surface because of permafrost. Here, icings form near large springs located in talik zones [*Alekseev et al.*, 2022; *Romanovsky*, 1973]. The high number of icings confirms that in the Selenga mid-mountains, even in areas marked as continuous permafrost on maps, numerous taliks exist.

The predominance of icings with areas up to 100,000 m^2 indicates that their primary water source is groundwater, which surfaces under cryogenic pressure arising from the seasonal freezing of rocks. For example, a spring with a constant flow rate of 5 liters per second (as described in [*Velmina*, 1970]) produces over 30,000 m^3 of water, or 32,000 m^3 of ice per season. According to [*Hydrogeology…*, 1970], the spring discharge rate in the Selenga mid-mountains rarely exceeds 10 liters per second. Given that the average thickness of icings in the Selenga mid-mountains is 0.7–1.5 meters [*Chernykh et al.*, 2024], the area of icings with a constant supply from deep groundwater sources at this rate should range from 25000 to 45,000 m^2. Of the mapped icings, 5100 (65%) are under 45,000 m^2.

The groundwater sources nourishing most icings in the region are buried alluvial gravel deposits, which are widespread in river valleys of the Selenga mid-mountains, lying at depths of 1.5 meters or more, with significant water reserves [*Kibanov et al.*, 1980]. There are also river water icings in riverbeds and floodplains of medium rivers, though these are few.

Meanwhile, in Figure 2, 1850 icings (about 24%) are shown to intersect with known and suspected tectonic fault zones, where icing areas mostly exceed 50000 m^2. This indirectly suggests that icings are fed not only by groundwater but also by springs discharging groundwater through hydrogeogenic taliks in fault zones. Such icings are classified as spring-fed icings.

Thus, around 65% of icings in the Selenga mid-mountains are groundwater-fed, while 24% are spring-fed. The genesis of 11% of icings could not be precisely determined via geoinformation analysis. It should be understood that these figures are somewhat conditional; often, icings are fed by groundwater from various aquifer horizons. Accurate data would require chemical analysis of icing-forming water sources, though this is challenging given the number of icings.

The dissected terrain of the Selenga mid-mountains results in an uneven distribution of icings. About 12% form in areas with an absolute elevation below 850 meters, i.e., in intermountain basins, while 49% form at elevations of 850 to 1000 meters (Figure 3). These heights correspond to foothills of ridges, and icings located between 900 and 1000 meters are generally found in the valleys of watercourses in ridge spurs, typically on terrain slopes of 2 to 4°, where 57.2% of all regional icings form. About 8.5% form on terrain with slopes around 1°.

Thus, the analysis of icing distribution in the landscape shows that about 66% (5100) are valley icings, 32% (2400) are slope icings, and slightly over 2% can be classified as watershed icings. Some of these are located above 1100 meters, as shown in Figure 3.

Cryogenic pressure, which depends on rock freezing depth, is a crucial condition for icing formation. Factors influencing freezing depth include cold-season air temperature and snow cover thickness [*Verkhoturov*, 2010]. A comparative analysis of air temperature and icing distribution for one year would not reveal patterns, as a dynamic approach is more suitable. Therefore, this question was not addressed in this study. Since a direct correlation between icing formation intensity and snow cover thickness has been established for Transbaikalia [*Verkhoturov*, 2010], this relationship was analyzed for the Selenga mid-mountains as well.

The speed and depth of freezing of rocks depend on the thickness of the snow cover. The deeper the seasonal freezing, the higher the cryogenic pressure. In the Selenga middle mountains, the greatest number of icings are formed in areas with thickness of the snow cover less than 40 cm (Table 1). These are mountainous areas covered with forest vegetation. At the same time, in intermountain basins with snow depth less than 20 cm total number of icings is less, but their area is larger. This fact indicates a significant influence of the snow cover on the intensity of icings processes, but additional research is required due to local differences.

This pattern is related to the absence of permafrost in many intermountain basins (see Figure 1) or the presence of a permafrost layer at depths far beyond the seasonal freezing layer (5–7 meters and deeper [*Hydrogeology…*, 1970]). Hydraulic connections within aquifers allow groundwater circulation without surfacing to form icings. At the foot of slopes, groundwater volume increases due to ridge runoff. Additionally, in these areas, permafrost and crystalline bedrock often act as aquicludes. Therefore, even with thicker snow cover leading to shallower rock freezing, icings are more numerous than where snow cover is minimal.

Thus, while snow cover influences icing formation intensity, in the Selenga mid-mountains, its role is less significant than the impact of terrain or permafrost-hydrogeological conditions.

4. Conclusion

Geoinformation analysis using a comprehensive data set identified key spatial distribution patterns of icings in the Selenga mid-mountains. Based on Landsat satellite imagery, over 7700 icings form in the study area under current natural and climatic conditions, with most being large and medium-sized.

Morphometric analysis and comparison of icing locations with tectonic fault distribution revealed that over 60% of icings are groundwater-fed, about 30% are spring-fed, sourced from deep aquifers through springs. River-fed icings are rare in the Selenga mid-mountains.

The terrain analysis showed that most icings (66%) are valley icings, forming at elevations of 850 to 1000 meters in intermountain basins and river valleys with slopes up to 4°. About 32% are slope icings.

Snow cover thickness in the Selenga mid-mountains has less influence on icing formation than factors like terrain and permafrost-hydrogeological conditions.

The obtained data reflect the general spatial distribution characteristics of icings in the Selenga mid-mountains and serve as a basis for further research.

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