RESEARCH PAPER

DISTRIBUTION OF ICINGS IN THE NORTHERN (RUSSIAN) PART OF THE SELENGA RIVER BASIN AND THEIR ROLE IN THE FUNCTIONING OF ECOSYSTEMS AND IMPACT ON SETTLEMENTS

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ABSTRACT. Icing is an integral part of the landscape in areas with permafrost. It is formed in winter in river valleys, along stream beds, in places of groundwater discharge and, unlike other objects of the cryosphere, is characterized by active dynamics. The main objective of this study is to identify the role and significance of icings in the functioning of natural systems of Russian part of the Selenga River basin, as well as their impact on settlements.

The first map of icings distribution was created based on Landsat imagery. In total, more than 15,500 icings were found. The highest concentration of icings is observed for forest landscapes. Icings in the forest-steppe belt are distinguished by their morphometric characteristics. They are often formed in giant areas of more than 1 km^2. Steppe icings account for about 8 % of all objects of the study area. Icings play an important role in the functioning of forest and, in particular, forest-steppe ecosystems, as they largely determine the redistribution of water flow in small watersheds.

During the period of increasing total water content, icings become a factor contributing to emergency situations. The potential risk of inundation has been established for 65 settlements in the Russian part of the Selenga River basin.

KEYWORDS: Icings, the Selenga River basin, runoff, mapping, NDSI, natural systems, anthropogenic systems, landscape

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INTRODUCTION

Icings formed in river valleys in the areas of permafrost distribution have been studied by scientists and research teams for more than a century. There are many publications devoted to the regularities of ice field formation and destruction (Podyakonov 1903; Tolstikhin 1974; Koresha 1981; Kravchenko 1985) the impact of icings on the river flow (Socolow 1975; Aufeis of Siberia 1981), spatial and temporal dynamics (Topchiev 1981; Alekseev 1973, 2007, 2016; Morse P.D 2015; Epsom T. et al. 2020), and other aspects. However, to a lesser extent, icings are studied in terms of their ecosystem significance, especially in regions where, at first glance, the role of icings in the functioning of the landscape sphere is insignificant. This includes Transbaikalia, including that part of the Selenga River basin. Icings and the processes associated with them have not been studied in the paper in as much detail as, for example, in the North-East of Russia or in the Baikal-Amur Mainline, because they do not cover large areas and volumes, but their role in the moisture turnover and some other processes of hydroclimatic nature is significant here.

The main goal of this paper is to assess the mapping of icings, taking into account the landscape approach with the study of their role in the ecosystems of the territory and their impact on the economic infrastructure and the environment. At the same time, making large-scale maps of the icings distribution is an important part of the work, since there are no available ones for the territory in question. Having a cartographic basis and databases containing the main morphometric characteristics of objects, it is possible to carry out a spatial analysis, to reveal regularities of icings distribution, its confinement to natural landscapes and location in relation to man-made objects.

The icings in the permafrost areas of are an integral part of the landscapes and, to some extent, markers of the climatic changes occurring in the cryosphere (Alekseev 2016). At the same time, the natural processes occurring in continuous permafrost areas are different from those manifested in areas where the permafrost has a sporadic, intermittent development (Chalov et al. 2017). In the areas of continuous permafrost, stretching in a wide belt across the northern continents from Alaska to Chukotka, icings are formed in the conditions of forest, swamp forest, and tundra landscapes. This is not the case at the southern border of the cryolithozone. Here, the range of natural complexes is considerably extended, up to semi-deserts and deserts. In Western Transbaikalia, in the Selenga River basin, significant areas of icing fields are ubiquitous in steppes (Chernykh et al. 2022). In Eastern Transbaikalia, icings are adjacent to the centers of desertification in the Chara River valley (Alekseev 2008). In different natural complexes, ice processes manifest themselves with their own specificity and the greater the diversity of facies, the greater the variations. In this respect, the Selenga River basin is considered to be a particularly interesting study area. Giant icings of river water and small spring icings — taryns — are formed here. There are great number of objects to study.

Another distinctive feature of the northern (Russian) part of the Selenga River basin is the relative development and settlement of the area. The icings are affecting economic activities and the population of the area. According to open sources, 13 cases of flooding of settlements and some infrastructure facilities (roads) by thawed icings were recorded in 2022. Therefore, when studying the role and significance of ice, it is necessary to pay attention to the aspects of ensuring safety of the population living in areas with intensive formation of icings.

MATERIALS AND METHODS

Study Area

The northern, Russian part of the Selenga River basin was chosen as the study area (Fig. 1). The total area is 148,060 km^2. The study area includes, fully or partially, the watersheds of the major tributaries, the rivers of Dzhida, Chikoi, Khilok, Temnik, and Uda. It is a combination of intermountain depressions and low- to medium-altitude mountain ranges. The peculiarity of the study area is a well-developed hydrographic network with a large number of small rivers and streams (Chernykh et al. 2021). The study area is typically characterized by the distribution of different types of permafrost rocks (permafrost). Thus, the central part, including the Selenga River valley and the adjacent areas with thick sandy and sandy loam sediments, is characterized by predominantly thawed soils. Insular permafrost is typical of the basins of the Dzhida (southern part), Khilok, Tugnui, Uda and other rivers in areas with mountain dissected terrain. Continuous permafrost is widespread everywhere in the mountainous parts of the Chikoi and Dzhida River basins (northern part of the basin). The diversity of cryogenic geological conditions in the area with a dense hydrographic network and harsh, sharply continental climate determines the specific features of the intensity of ice formation processes.

Satellite images

Multispectral satellite images from Landsat 4-5, Landsat 8 and Sentinel were used as input data for the process of icings mapping. Landsat 8 and Sentinel images were used to determine the current location of objects in river valleys and to prepare maps of their current state. Twenty Landsat 8 scenes and ten Sentinel scenes were acquired from the servers of the US National Geological Service (https://earthexplorer.usgs.gov/). The images were selected so that the area of snow cover on them was minimal, and the imaging dates should not be far from the beginning of the icing fields thawing. For the lowland areas of the central part of the Selenga River basin it is late March – early April, for the middle mountains of the Dzhida and Chikoi Rivers basins, it is late April – early May. Under these conditions, even small ice fields with the size of 1-2 pixels (with the resolution of 60 m per point) are visually distinguishable on the obtained images. We used images from 2020, in some cases, when there were no images of proper quality from 2020, we used scenes from 2019. Comparison of the same scenes shows the similarity of natural and climatic conditions in spring 2019 and 2020, which in general satisfies the mapping tasks.

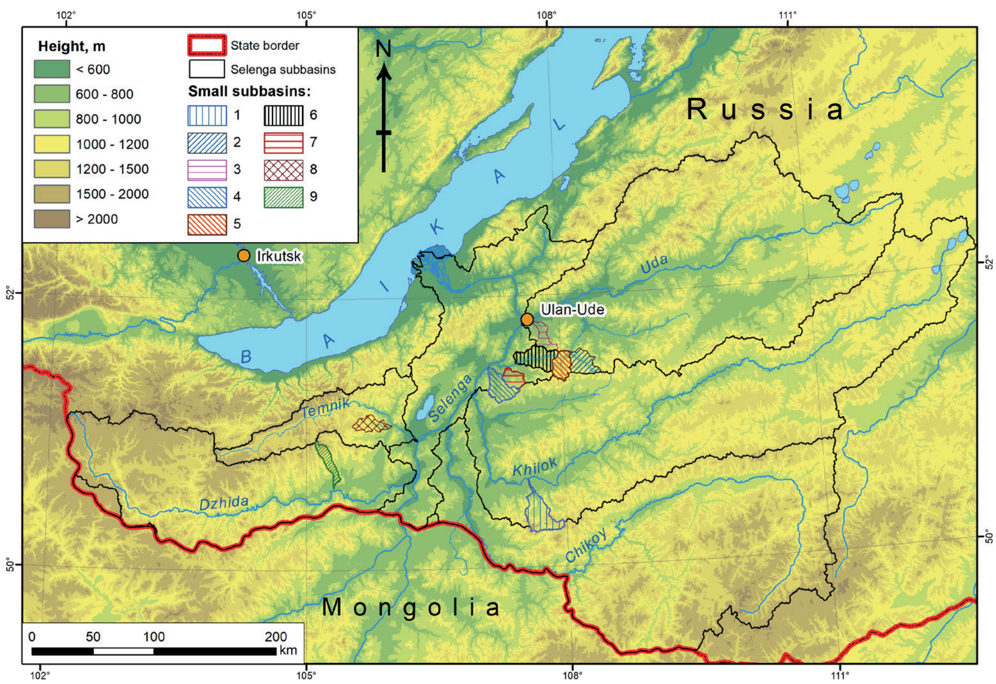

Fig. 1. Study area. Numbers indicate key sites (small watersheds): 1 - Vorovka, 2 - Kuytun, 3 - Kokytey, 4 - Shabur, 5 - Tarbagatai, 6 - Zhirim, 7 - Bichura, 8 - Urma 9 - Tsagatuy

Data analysis

The study used the NDSI index to determine the localization of the icings. The Normalized-Difference Snow Index, or NDSI, is an index for the interpretation of snow-ice objects (Hall 1995; Gagarin 2020; Brittney 2021). Its calculation is based on the difference in the reflection of radiation between the visible green (Green) and shortwave infrared (SWIR) parts of the spectrum. The index can be calculated in various GIS with a built-in algorithm for raster images (Raster Calculator). NDSI is calculated using the formula NDSI = (Green-Swir1)/(Green+Swir1).

This index is widely used by researchers in the interpretation of snow-ice objects, including icings, from multispectral satellite images. To facilitate the search process, various algorithms are used, allowing more or less automation of the process. In most cases, a buffer zone is pre-determined around watercourse thalwegs, within which calculations are performed, an output mask by NDSI threshold values and the reflection coefficient in the infrared range (Makarieva et al. 2019) are created, which allows to successfully distinguish ice from snow in watersheds later on. The above approach can be effectively applied to detect large ice deposits in those areas where they are formed on medium or large rivers. With the overwhelming majority of watercourses being small rivers and streams, the very process of buffer definition already becomes a complex and laborious work.

The results of the analysis of various publications indicate that semi-automatic methods of icings interpretation in combination with expert assessment are mostly used in large-scale icings mapping (Shikhov et al. 2020). For territories with complex, dissected topography, where the vast majority of icing fields are relatively small in size, such interpretation methods are the most suitable and give the most reliable results.

Field data

Individual icings located in different, small watersheds were studied by field expedition methods. Detailed investigations, which included ice field surveys from an unmanned aerial vehicle (UAV) with additional ground referencing, ice measurement surveys, ice drilling and ice volume counts, photographic recording, etc., covered 15 medium and large ice fields in 9 small watersheds (Fig. 1). Geological and geomorphological features of the study area, the role of icings in the ecosystems of the territory, and potential risks of minor flooding of settlements and infrastructure facilities were taken into account as criteria for selecting key sites. Meteorological data and quantitative runoff characteristics (for the key site in the Kuitunka River basin) were obtained from the Tarbagatai meteorological station (hydrological post).

RESULTS

Creation of thematic maps of hydrological processes is an important part of the study of water resources (Kortney et al. 2020). The icings mapping within the northern, Russian part of the Selenga River basin was performed with the use of Landsat and Sentinel satellite images. The 2019 and 2020 imagery was used in the study process, so the resulting map of the icings (Fig. 1) reflects the current location of the ice fields. The original map (GIS layer) is a set of polygons showing the actual position and morphometry of the icing fields.

There are 15547 objects marked on the map (in the vector layer), and attribute tables contain their basic planned morphometric characteristics. The total area of the icings as of 2020 is 364.79 km^2. Table 1 shows the distribution of the icings in the basins of the major rivers of Selenga tributaries.

According to the main morphometric characteristics, 6,117 objects belong to small and medium icings (S = 0.1 – 10 thousand m^2), 8,878 – large (10 – 100 thousand m^2), 429 – very large icings (100 – 1000 thousand m^2). Very small icings, with an area of less than 100 m^2, are definitely present within the territory, but their interpretation on medium resolution space images, especially in the forest belt, is complicated. We recorded one giant icing (Dzhida River basin).

Ice measurement surveys to determine ice thickness were conducted in the key study areas. The results of measurements show that the thickness of ice fields can vary from 0.45 to 3.5 m, depending on the valley structure and intensity of the icings processes. The average thickness of the icings in the study area ranges from 0.8 to 1.3 m.

Taking into account the experience of colleagues who have performed icings mapping within a region similar in area and number of objects (Brombierstäudl et al. 2021), we developed an icings map based on the «Icing» layer, which is a generalized image for the convenience of presentation. All the icing deposits in a 10 × 10 km cell are united by one scale symbol, denoting the icing coverage (S of the icing cover to S of the area ratio) for each specific cell. This allowed, on the one hand, to preserve the ideas about the localization of objects within the study area and on the other hand, to avoid "blurring" the correct perception of the information about the mapped objects.

Cartographic methods have been used to determine the difference in the icings coverage in the study area. It is highest in the Dzhida River basin, the territory of which is characterized by dissected relief and the presence of a large number of watercourses. Here this indicator can

Table 1. Icings by the basins of major tributaries of the Selenga River

	Rivers	Basin area, km^2	Number, pcs.	Total area, km^2	Volume, km^3	Ice coverage, %
1	Selenga*	16,926	69	2.8	0.003	0.016
2	Uda	34,800	2,929	88.41	0.079	0.254
3	Khilok	38,500	4,484	86.52	0.095	0.224
4	Chikoy	34,700	5,462	107.71	0.118	0.310
5	Dzhida	18,894	2,383	74.75	0.097	0.395
6	Temnik	4,240	220	4.6	0.003	0.108
	Total	148,060	1,5547	364.79	0.395	0.217

*- Russian part of the catchment basin (without the basins of major tributaries).

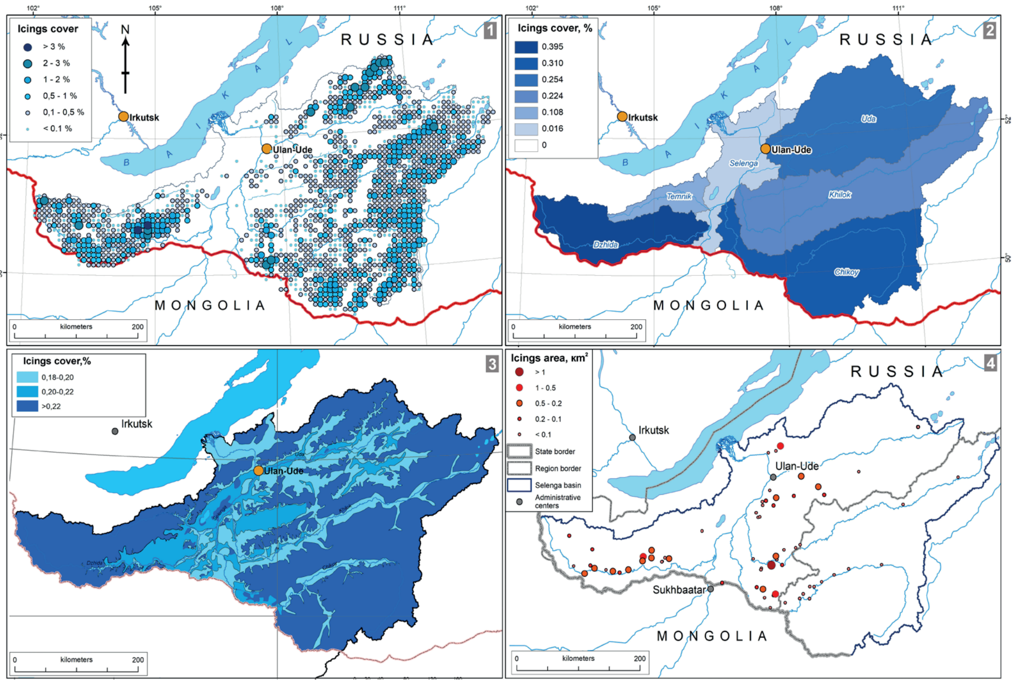

Fig. 2. Icings in the northern (Russian) part of the Selenga River basin: 1 - location card, 2 - icings coverage by the Selenga River tributary basins, 3 - icings coverage by landscape (altitude) belts, 4 - potentially dangerous icings

reach 0.4 %. The minimum icing coverage (0.01%) is observed in the central part of the Selenga River basin (not including basins of major tributaries), where icing is typical only for valleys of small rivers of Tsagan-Daban range spurs. Individual, small objects were observed during field studies in deep ravines and gullies in Medvedchikovo, Oditsar, Mengei and some other hollows.

Comparison with landscape maps (Atlas of Transbaikalia 1967; The ecological atlas... 2015) allowed us to establish quantitative characteristics of the icings distribution in different natural complexes by altitudinal belts. The forest belt (up to 12.2 thousand) is distinguished by the greatest amount of the icings, as it occupies the largest area. There are many facies in the Selenga River basin, depending on the absolute height, steepness and exposure of the slope, and the nature of vegetation. Icings are formed in narrow gaps almost everywhere in mountain-taiga and sub-taiga landscapes. Here they have small areas, 5–10 thousand m^2, with a thickness of 1–2 m. In the forest-steppe belt of low mountains, in intermountain depressions, where mouth parts of small and middle river beds are located, at least 2.2 thousand icing deposits are formed. They are larger than those in forests, and in some cases are up to 4–5 m thick. About 1 thousand icing deposits are distinguished in steppe landscapes of the territory. Ice-covered steppes are not exactly a typical phenomenon, but icings are ubiquitous, although not very large, in South Siberia and Mongolia. The distribution of the icings over natural complexes determines the differences in icings coverage (Fig. 2, 3).

Here, the icings are formed in valleys of numerous small rivers and along streams. At the same time, areas and volumes of the icings in river valleys, flowing in the forest-steppe conditions, are much larger than those in the forest belt. The icings are also observed in the steppes of the northern (Russian) part of the Selenga River basin, but they are of limited development. These are mainly spring icings.

DISCUSSION

The cartographic analysis established the similarities and differences in icing cover in the basins of the major tributaries of the Selenga River. They are determined by physical and geographical conditions. In the Uda and Khilok River basins, which are similar in size, the icings areas and the icing coverage coefficients are approximately the same. In the Chikoi River basin, which is approximately the same size as the Uda and Khilok Rivers within the territory of Russia, the total area of the icings is 20 km^2 larger.

The most important factor determining the intensity of ice formation is the type of permafrost rock characteristic of the territory. This is confirmed by the comparison of the permafrost distribution maps (Geocryology of the USSR 1989; Bazhenova 2018) with the obtained map of the icing coverage of the territory. The greatest number and the maximum total area of the icings (relative to the basin area) is observed in the Dzhida River basin, where continuous permafrost is widespread. The number of icings increases in the southeastern part of the Chikoi River basin, which is characterized by the same type of permafrost, in the mountainous part of the Uda River basin. In the head watershed of the Selenga River, in the estuaries of the valleys of large tributaries, the concentration of the icings is minimal, since thawed soils are common here.

As part of natural complexes with traces of the lower boundary of the cryosphere in their lithogenic base, the icings perform important habitat-forming and habitat-protecting ecosystem functions. At the same time, the ecosystem significance of icings is more pronounced in the forest belt and floodplain landscapes of the mountain forest-steppe. Thus, with an average thickness of 1.5 – 2 m, the icings in floodplains and on low terraces of small rivers in the Selenga middle mountains may persist until early June. Observations in the key area, where sensors were installed to record the main climatic parameters of the environment, showed that under current climatic conditions the process of icing formation starts at the end of December and ends at the end of March. For example, in 2022, the icings in the upper reaches of the Vorovka River, the beginning of formation of which was recorded on December 23 at air temperatures below – 20 °C, had an area of 0.074 km^2 and a volume of 100 thousand m^3 by the beginning of thawing on March 30. Thus, the ice fields mid-mountain forest-steppe landscapes exist up to 5 months, 2 of which are at maximum area with a constant increase in volume. In addition, the spatial and temporal dynamics are characterized by a year-to-year shift of ice fields along stream channels within a wide range, and characteristic icing glades are well defined in the topography and recorded in floodplain vegetation.

The impact of icings on forest ecosystems, including mountain taiga, is even more pronounced. There, they are actually formed everywhere in narrow, often V-shaped valleys with permanent watercourses, rivers or streams. In the forest belt, in the Selenga River basin, where the upper boundary of spring icings spreads up to 1550 – 1600 m, even small in thickness icings may persist until the end of June. This determines a special microclimate, topography and hydrological features. The icing glades in the depressions are usually waterlogged, and the vegetation period of herbaceous vegetation starts belatedly.

The icings in the northern (Russian) part of the Selenga River basin play an important role in supplying river runoff. During the mapping process, 1,400 small rivers (3rd order) and more than 3,300 streams were identified within the territory. The runoff of these watercourses from April till June depends almost entirely on the thawing of the ice fields in their valleys. Icings accumulate a whole winter runoff. Calculations of the icing runoff, made using Landsat satellite images, data from a gauging station and Tarbagatai weather station (2000) through the example of small catchment area of Kuitunka River show that by the middle of April about 1540 thousand m^3 of ice is contained in the icings fields, which makes 8.4% of annual flow of Kuitunka River. Similar values were obtained by calculation for other small watersheds in the key study areas. Thus, in total, not less than 0.6 km^3 of ice is contained in the icings of the territory by spring. Part of this melting water flows further into medium and large rivers, but part of the runoff, which is very important, is taken for the agriculture needs. The water of small rivers and streams is actively used by the local population and agricultural enterprises for irrigation of cultivated meadows in the river valleys. For this purpose, entire networks of irrigation systems, which allow transferring water over distances of dozens of kilometers, were created using traditional technologies as far back as the last century. Due to the melting of the icings, providing almost uninterrupted flow of small rivers and streams during the period when precipitation is very limited (Garmaev at el. 2020).

Along with the important ecological significance, the icing processes under consideration are also the factors of geo-ecological risks associated with the threats of flooding. The potential threats of flooding in this case should be understood as the probability of excessive development of the ice field of an icing, in which case residential houses, buildings on household plots, infrastructure facilities, etc. are affected by the natural process. A total of 350 settlements, including towns, villages, large summer houses (farms) included in municipalities, were considered in the Russian part of the Selenga River basin, including the Republic of Buryatia (RB) and Zabaykalsky Krai. When identifying the icing threats, not only the territory included in the settlement's boundaries, but also infrastructure facilities adjacent to the settlement, farms, roads, railroads, power lines, etc. were taken into account. The risk was determined by the actual proximity or presence of the icings in the boundaries of the settlement.

Potential threats of underflooding by icings have been established for 65 localities within the Selenga River basin (Fig. 2, 4), of which 51 are in the RB, including 3 cities (Fig. 3). In Ulan-Ude, the capital of the Republic of Buryatia, residential houses in Arshan, Verkhnyaya Berezovka, Divizionnaya Station, Zabaikalsky and Erhirik settlements (part of the agglomeration) are flooded by the icings. Zakamensk, located in the Dzhida River basin and characterized by unfavorable environmental conditions (Garmaev et al. 2016), is also affected by the icings. The Icings are also formed in the center of the bordering town of Kyakhta. In Zabaikalsky Krai, the potential threats of underflooding by the icings have been established for 14 settlements. A study of the dynamics of individual the icings over the period from 2000 to 2020 in small watersheds within the Russian part of the territory showed that, depending on the climatic cycle, the areas of the icings can vary by 6 times (Chernykh et al. 2021). Thus, the current location of the potentially hazardous icings determines the risks of underflooding both in the current natural-climatic situation and with further increase in the total water content.

Combating icings and protecting settlements from underflooding is becoming an increasingly urgent task in the region due to the onset of a high-water climatic cycle.

Fig. 3. Icings in the settlements: 1 – Nikolaevsky, 2 – Burnashevo, 3 – Petropavlovka, 4 – Bichura
Photo images from an unmanned aerial vehicle

The long period of drought in Transbaikalia has led to the dilapidation and partial destruction of a number of icing protection structures (dams with sluices), which requires their inventory, repair and restoration, and the construction of new ones. The experience of 2022 has shown that it is necessary to purchase special equipment, which allows reducing the risks of underflooding where the icings have already reached significant volumes. In these cases, sawing ice to create ditches to divert water is almost the only way to protect against flooding, and it must be done until the ice fields begin to melt.

The main hazard of icings is that forecasting the intensity of their development and location in relation to populated areas and infrastructure objects is an extremely difficult task, since a large number of factors, from precipitation to tectonics, must be taken into account (Romanovskii 1973; Shesternev and Verkhoturov 2006). As studies show, the spatial and temporal dynamics of icings is expressed in their extreme variability (Alekseev 1987). Therefore, it is necessary to scientifically substantiate and create a modern monitoring system for icings potentially hazardous for settlements and infrastructure objects.

Thus, the icings formed in the northern (Russian) part of the Selenga River basin play an important role in balancing natural and anthropogenic-transformed systems, as well as in maintaining a favorable environmental situation in the territory, which differs in its characteristics from the hard-to-reach areas of the North or Northeast Russia, where giant icings are formed, which have been studied by various researchers for many years.

CONCLUSIONS

Icings are fascinating objects of the cryosphere. In the northern (Russian) part of the Selenga River basin, they are formed in forest, forest-steppe, steppe and even, in fact, semi-desert (dry-steppe) landscapes. This is one of the peculiarities of Transbaikalia — the formation of so-called permafrost or cryoarid landscapes (Taisaev 2004). Cryogenic processes are observed throughout the region, especially during high-water climatic cycles. It should be noted that large-scale GIS mapping of the icings has not been conducted in this part of the territory before, which is one of the factors explaining the novelty of this work.

The results of the study:

1. The first large-scale map of the location of the icings in the northern (Russian) part of the Selenga River basin has been compiled. The peculiarity of the map is that it shows the maximum number of objects for this mapping scale — more than 15.5 thousand. With a frequency of the icings formation is 75% and higher, which is typical for the study area according to the analysis of multi-temporal satellite images, the map is relevant not only for the specific and nearest years, but can be used for long-term observations and research of icings.

2. Vector data and basic, planned morphometric characteristics of the icings in the transects of the vast area have been obtained. These data can be used in studying icing dynamics, identifying the dependence of icing formation intensity on various environmental factors, as well as in applied activities, for example, in planning the organization of the economic activity within an area.

3. The landscape approach to the study of icings allowed us to determine their place, role and significance in the natural systems of the study area. New up-to-date views on the areas of the icings formation for varying altitudinal belts were obtained. The Icings in the taiga and sub-taiga landscapes form the microclimatic features of the mountainous areas. The Icings in the forest-steppe belt contain maximum water reserves. Up to 8 % of the icings are confined to steppe landscapes of the territory. Icings play an important role in providing and maintaining the runoff of small rivers and streams, numbering least 5 thousand within the study area.

4. Icings have a negative impact on the man-made systems of the territory, primarily on the settlements and infrastructure facilities. This impact is expressed in the form of underflooding, which occurs during the cold season in early spring and is therefore difficult to remedy. In the northern (Russian) Selenga Basin, flooding risks have been identified for 65 communities and numerous infrastructure facilities.

The study of icings, in various aspects, remains urgent. This is especially true of the areas on the southern border of permafrost distribution. In the past, there has been little attention paid to icings, but there is little research at present. At the same time, interest in these objects of the Earth's cryosphere is growing, and modern technical capabilities, including the use of space images and drones, bring the study of icing processes to a new level.

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