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SNOW COVER AND GLACIERS

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SNOW HAZARD ASSESSMENT ON SAKHALIN ISLAND

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The information about the snow hazard processes and phenomena occurring in the urban areas of Sakhalin Island is presented. The snow hazard embraces all kinds of damage that snow and ice may inflict as such or in combination with the weather conditions. The major harm for the population and economy of Sakhalin Island is caused by snowfalls, snowstorms, snow patches, snow loads, and avalanches. The paper presents a method for snow hazard assessment based on qualitative evaluation of the effects of these hazards with specific characteristics employed: for avalanches – the areal percentage of exposure of a territory to avalanches, for snow loads – the peak loads, for snowstorms – the average duration of a snowstorm per winter, for snowfalls – the maximum amount of precipitation within 12 hours, for anthropogenic snow patches – the volume of snow at the end of winter. The paper presents a schematic map of the snow hazard for the urban areas of Sakhalin Island. The following settlements: Okha, Shakhtersk, Uglegorsk, Makarov, Kholmsk, Yuzhno-Sakhalinsk, and Korsakov – are exposed to the maximum degrees of the snow hazard on Sakhalin Island. The majority of these settlements are situated on the sea coasts of southern Sakhalin, where the high degree of snow hazard is caused by the combination of hydrometeorological and geomorphological conditions.

Snow hazard, snowfall, snowstorm, snow load, avalanche, anthropogenic snow patch

INTRODUCTION

The snow cover and the processes related to it exert significant influence on the economy of the Sakhalin region. Formation of a stable snow cover requires that safety measures should be taken to protect the infrastructure facilities, residential buildings and houses, production facilities, and the population of the region. The annual harm inflicted by snow is difficult to assess. The extent of the impact of heavy snowfalls, snowstorms, snowdrifts on roads, etc., correlates with the degree of urbanization of the territory hit by these phenomena. Snowfalls result in the need for clearing the territories from snow and preparing special sites for keeping snow loads, thus necessitating significant expenses. For example, according to the Sakh.com information agency, in the winter season of 2015/16, 86.5 million rubles were allocated for the winter maintenance of motor roads in the Sakhalin region. Only one of the local companies of Yuzhno-Sakhalinsk involved in snow removal reported to have removed about 630 thousand m^3 snow from the area of 70 hectares and placed it on anthropogenic snow patches, for the execution of which it charged 64.2 million rubles.

Comprehensive assessment of the impact of the processes and phenomena related to snow will allow substantiation of the economic costs of snow removal and utilization and making the urban territory safer for the population.

The unfavorable effects related to snowfalls may be totaled in the notion of the snow hazard of a territory.

The snow hazard indicates a multitude of unfavorable or disastrous phenomena resulting from the fall of solid atmospheric precipitation, from formation, re-crystallization and destruction of the snow cover under natural or anthropogenic conditions [*Alekseev, 2005*]. In foreign literature, the same term is used [*Rooney, 1967*].

In this study, the processes and phenomena having the most unfavorable effects for the economy of Sakhalin Island are considered (Fig. 1).

Under the term 'hazard', the authors understand the index of activity of the dangerous processes occurring in the given territory independently of the degree of their anthropogenic development [*Kazakov, 2015*].

The objective of this study was to examine the effects of the fall of solid atmospheric precipitation on urbanized territories and to assess the degree of their impact on the town management by the example of Sakhalin Island.

SNOW-CAUSED HAZARDOUS PROCESSES

Heavy snowfalls

Heavy snowfalls are characteristic of many districts of Sakhalin Island. For example, in the towns of

Fig. 1. Hazardous processes and phenomena related to snow on Sakhalin Island.

a – the streets of Yuzhno-Sakhalinsk after the snowstorm of 02.03.2013; *b* – the anthropogenic snow patch in Yuzhno-Sakhalinsk, 27.05.2009; *c* – breakdown of the roof of a school building in the village of Pyatirechye, 2009 (the photo was borrowed from the website http://sakhvesti.ru/); *d* – clearing a motorroad from avalanche obstruction, Yuzhno-Sakhalinsk–Nevelsk highway, 05.02.2014.

Poronaisk, Uglegorsk, Makarov, Dolinsk, Yuzhno-Sakhalinsk, and others, the intensity of snowfalls may reach 30 mm and more within 12 hours.

In accordance with the terminology used by Rosgidromet (Russian Committee for Hydrology and Meteorology), heavy snow means heavy solid precipitation (snow or shower snow) with the amount of precipitation not less than 20 mm within a period of 12 hours or less [*Working Document 52.88.699-2008*]. Such snowfalls cause large increment in the snow cover depth: the depth of the snow cover in the streets of Yuzhno-Sakhalinsk after snowstorms is 30–40 cm on average. However, snowstorms occur practically every year, after which the depth of the snow cover reaches 50–100 cm and more, and in snowdrifts in some streets, the snow depth reaches 1–3 m. They mainly cause indirect economic damage, like lack of transportation and the necessity of clearing the city streets. For example, according to the data provided by the city management department of Yuzhno-Sakhalinsk, clearing of the city territory after snowstorms requires the operation of about 300 specialized motor vehicles.

Snowstorms

In accordance with the terminology used by Rosgidromet, a snowstorm is transport of snow from the underlying surface (often accompanied by snowfall from clouds) by a strong (not less than 15 m/s) wind and with meteorological visibility not more than 500 m, lasting at least 12 hours [*Working Document 52.88.699-2008*]. In the territory of the Sakhalin region, criteria of hazardous hydrometeorological phenomena are used, developed considering the local natural and climatic conditions on the basis of the standard list of hazardous natural hydrometeorological phenomena, agreed upon with Rosgidromet and the government of the Sakhalin region. In accordance with these criteria, for the territory of Sakhalin Island, a severe snowstorm is a total or ground snow-

storm lasting 12 hours and longer at the maximum wind velocity 20 m/s and more and visibility of less than 500 m [http://sakhmeteo.ru/ourforecasts/oya.php]. In our opinion, snowstorms with the wind velocity of even 15 m/s present a significant hazard for the population and for the local economy; therefore, in evaluating the snow hazard of the territory of Sakhalin Island, the authors used data on snowstorms accompanied by the wind velocity of more than 15 m/s.

Severe snowstorms last most on the coasts of Sakhalin Island. For example, in Kholmsk the duration of snowstorms exceeds 600 hours during a winter season [*Pilnikova, 1990*]. The damage from snowstorms on Sakhalin Island consists, apart from snow deposited in the city territories and on the wires, in partial or complete destruction of roofs and building windows, and motor vehicles, and in the massive damage of trees. Every year, snowstorms are the cause of transport stoppage blocking transportation among the island towns and cities, airplane and ferryboat transportation between the island and the continent.

Anthropogenic snow patches

Anthropogenic snow patches are areas for storing snow masses removed from the territories cleared from snow. On Sakhalin Island, the snow patches are located in eight settlements and along linear energy and transportation objects. The largest snow patch is located in Yuzhno-Sakhalinsk: more than 1 million m^3 snow is delivered there during a winter season. The total area of the lands occupied by the anthropogenic snow patches exceeds 19 hectares only in Yuzhno-Sakhalinsk. Storing snow within city limits leads to occurrence of hazardous exogenous geological processes, such as flooding, water logging, frost heaving, and a rise in the level of ground water. Snow patches exert a negative impact on the condition of the environment [*Lobkina and Gensiorovsky, 2012*], as the snow removed from the city streets contains contaminants which penetrate the ground during snow melting and migrate with the melted water. City rubbish gets to the snow patches as part of the removed snow, turning the snow patches into unauthorized dumps.

Snow loads

Accumulation of large masses of snow on building roofs after snowfalls results in formation of excessive snow loads. Breakdowns and damage of roofs in the territory of Sakhalin Island have been recorded over the recent decade in 2009, 2012, 2013, and 2015.

The estimated amounts of the snow load per 1 m^2 of the horizontal surface of the land for the administrative centers of the island vary from 3.2 kPa (Smirnykh) to 6.0 kPa (Dolinsk, Yuzhno-Sakhalinsk) [*Gensiorovsky et al., 2011*], while the maximum amount of the snow load increment per one snowfall varies from 1.0 kPa (Smirnykh, Korsakov, Aniva) to 2.5 kPa (Tomari, Dolinsk, and Yuzhno-Sakhalinsk).

Avalanches

Despite the primarily low-mountain and middle-mountain relief, the territory of Sakhalin Island is characterized by high avalanche activity. Avalanches move down every year, and not only in the mountainous part of the island but also from the cliffs of the sea and river terraces taller than 10 m and from hills of the anthropogenic origin. About 400 km motorways and railways are exposed to the avalanche hazard in the avalanche hazard zones of Sakhalin Island, as well as 54 settlements (8 towns and 46 villages). The areal exposure to avalanche processes varies from 1 to 45 % (for example, that of Kholmsk is 29 % and that of Nevelsk is 45 %).

Avalanches regularly damage buildings, structures and transport vehicles and form accumulations of snow in settlements and around infrastructure facilities. Apart from the economic damage, avalanches cause casualties: in the period from 1905 to 2016, more than 1100 people got caught in avalanches, with more than 700 of them killed [*Kazakova and Lobkina, 2013; Podolskiy et al., 2014*].

The methodology of assessing the snow hazard

Four categories of the snow hazard have been classified for each process considered (Table 1). The parameters for categorizing the snow hazard are based on the qualitative assessment of the effects of

Table 1. **Parameters of snow hazard categories**

Processes and phenomena	Parameter	Measurement unit	Snow hazard category and the score			
			Low, 1 score	Medium, 2 scores	High, 3 scores	Very high, 4 scores
Heavy snowfall	Maximum amount of solid precipitation within 12 hours	mm	<10	10–20	20–30	>30
Snowstorm	Maximum duration in winter	h	<200	200–400	400–600	>600
Anthropogenic snow patch	*For towns* – the volume of stored snow at the time of the patch closure	thousand m^3	<200	200–400	400–600	>600
Snow load	Maximum weight of snow cover per 1 m^2 of surface	kPa	<1	1–3	3–5	>5
Avalanche	*For towns* – areal exposure of the territory	%	<10	10–20	20–40	>40
	For the island territory – medium amount of avalanche catchments per 1 km of linear length of a valley or shore	event	<1	1–5	5–10	>10

these processes and phenomena on the city territory. For each process considered, a specific parameter was selected, most fully reflecting its characteristic.

Snowfalls. As a criterion for assessment of the degree of impact of heavy snowfalls, such a parameter was used as the maximum amount of solid precipitation lasting at least 12 hours. Due to the lack of the mean annual values, the data relating to the period of 2005–2016 were used.

Snowfalls with the amount of precipitation equal to 18–19 mm lasting at least 12 hours were also considered by the authors together with heavy snowfalls, as, in our opinion, the 1–2 mm difference is negligibly small. Such snowfalls are referred to the 'medium' degree of the snow hazard. The authors referred snowfalls, classified, in the terminology of Rosgidromet, to very heavy snowfalls (see above), i.e. with the amount of precipitation 20 mm and more lasting 12 hours and longer to a higher degree of the snow hazard. With the average density of fresh snow equal to 100–120 kg/m^3 (the value of snow density was obtained by the authors based on nature observation data in Yuzhno-Sakhalinsk) being 20 mm of precipitation corresponds to a layer of snow equal to 15–20 cm. When such snowfalls occur, transport traffic is suspended outside settlements. The authors referred snowfalls with precipitation over 30 mm lasting 12 h and longer to a very high category. For example, such amount of precipitation is equal to 25–30 cm of freshly fallen snow (with the average snow density 100–120 kg/m^3), which for the territory of Yuzhno-Sakhalinsk constitutes nearly 50 million m^3 of snow (the city area is 164 km^2).

Snowstorms. Maximum duration of snowstorms in a winter season was selected as a criterion of the degree of impact of severe snowstorms. In the authors, opinion, such parameters as the intensity or volume of the snowstorm transport are less representative due to the extremely scarce factual data on these parameters for the territory of Sakhalin Island and the imperfections of the methodology of calculating the intensity or volume of the snowstorm transport [*Lobkina et al., 2012*]. Due to the absence of observations over snowstorms now, we used data from [*Lazareva, 1985*].

Snow loads. The maximum amount of snow load is the determining parameter for qualifying a snowfall. The authors identified only high and very high snow hazard categories, which is related to high values of the snowfall (more than 3.2 kPa), characteristic of the territory of Sakhalin Island (to compare, in accordance with [*Construction Regulations 20.13330.2011*], snow loads are taken to be equal to 0.8–3.2 kPa for the larger part of Russia).

Anthropogenic snow patches. Anthropogenic snow patches were evaluated by the volume of snow stored there at the moment of closure at the end of the winter season, as this characteristic will affect the probability of occurrence of hazardous exogenous geological processes in the surrounding territory and the extent of its contamination.

Avalanches. To evaluate the avalanche hazard of a certain territory, it is reasonable to use such a parameter as areal exposure to avalanche processes (the ratio of the area exposed to the impact of avalanches, irrespective of avalanche characteristics, to the total area of a certain territory, for example, of that of a settlement). It is difficult to use the data regarding the volume and recurrence of avalanches to evaluate the avalanche hazard for a large territory. For example, it is difficult to compare the avalanche hazard of two areas, in one of which avalanches amounting to 1,000 m^3 move down 2–3 times during a winter season, while in the other area an avalanche amounting to 100,000 m^3 moves down once every 20–25 years. Therefore, the authors used areal exposure of the territories of cities and towns to avalanche processes as a criterion of the avalanche hazard. However, to calculate this characteristic for the entire territory of Sakhalin Island is a hard and long work, as it is necessary to carry out mapping of hundreds of thousands of avalanche catchments in the scale of at least 1:25 000 to correctly assess this value. Therefore, in evaluating the avalanche hazard of the island territory (except cities), the authors used such a parameter as the average number of avalanche catchments per linear length of a river valley or of the seashore equal to 1 km. This value is the highest on seashores and in the mountainous parts of the island (Eastern Sakhalin and Western Sakhalin mountains).

Due to the absence of hydrometeorological stations (HMS) in the mountainous areas, assessment of the hazard of heavy snowfalls and snowstorms and comprehensive evaluation of the snow hazard for Sakhalin Island were performed only for plain territories. To evaluate the degree of the hazard of heavy snowfalls for plain territories, the HMS data were interpolated considering the climatic zoning and the island relief.

Each category of the snow hazard was assigned a score ranging from 1 to 4 (Table 1). Based on the results of the snow hazard assessment, scores relating to each parameter were summed up, which allowed us to indicate the towns or regions of the island characterized by the highest total snow load due to the impact of the processes in question.

Comprehensive assessment of the snow hazard of Sakhalin Island has been carried out by the authors separately for the cities and towns and for the island territory.

RESULTS AND DISCUSSION

Based on the comprehensive evaluation of the snow hazard, schematic maps of the snow hazard have been composed for each process considered (Fig. 2).

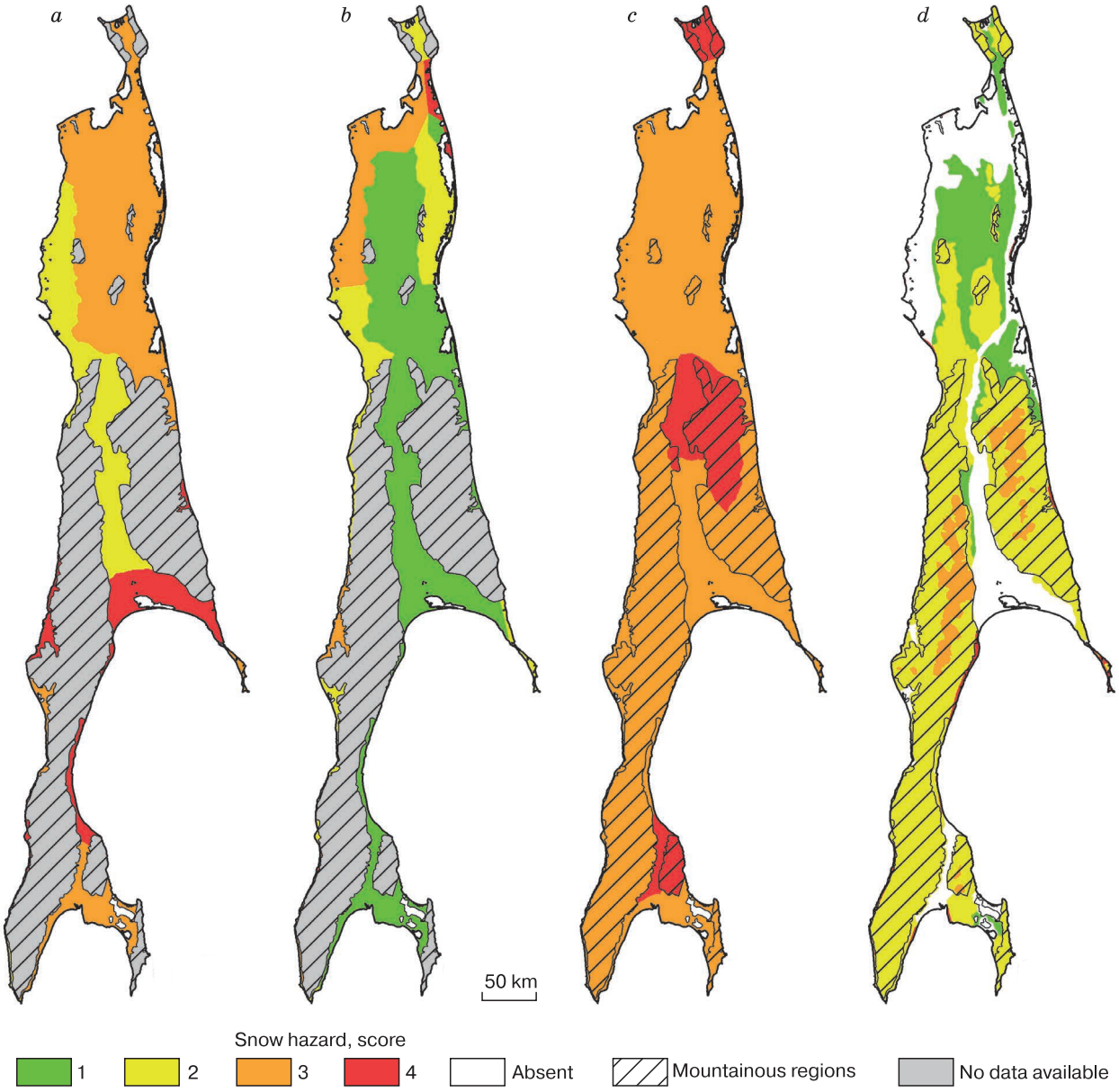
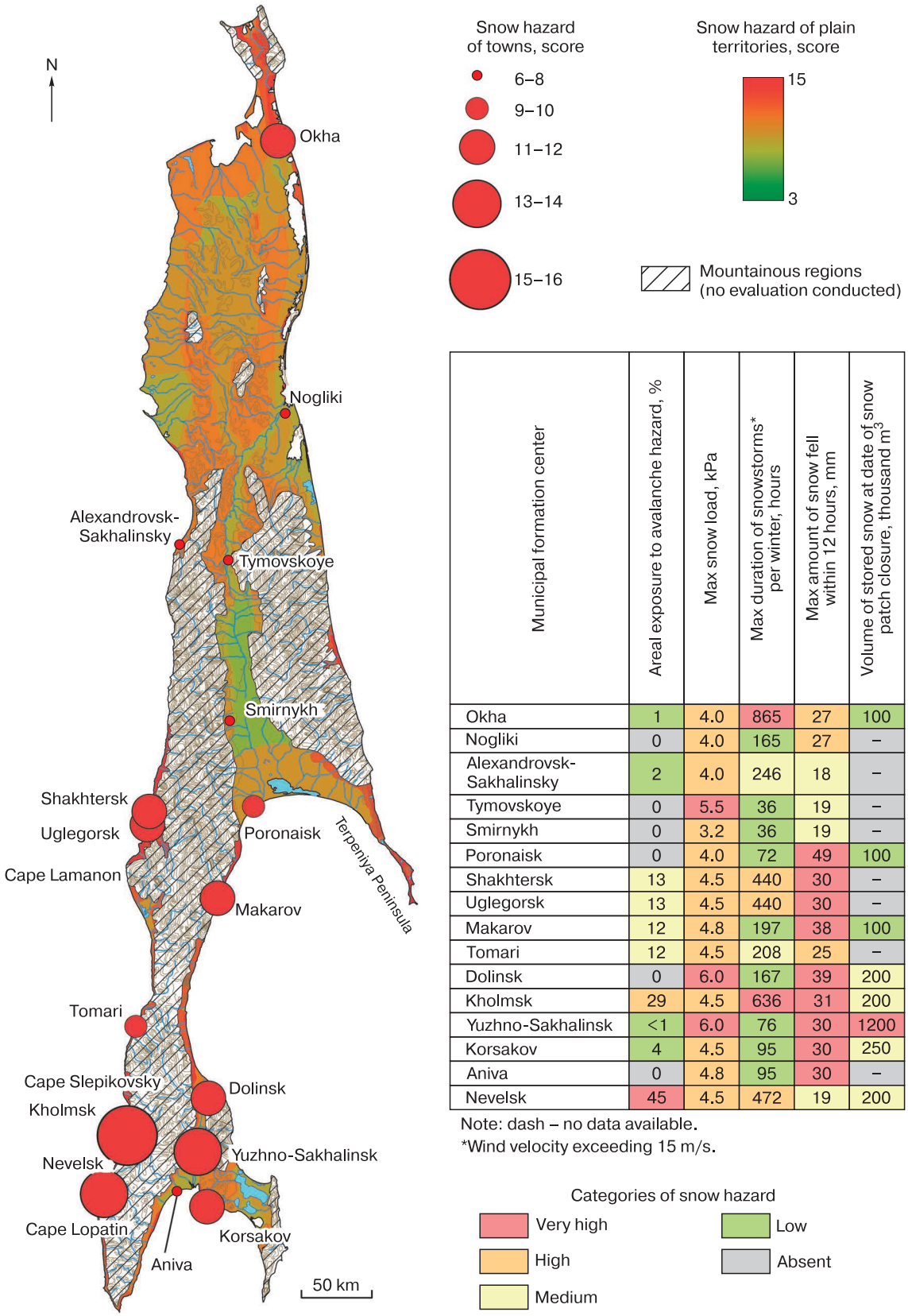


Fig. 2. The snow hazard on Sakhalin Island caused by heavy snowfalls (*a*), snowstorms (*b*), snow loads (*c*) and snow avalanches (*d*).

The complex evaluation of the snow hazard resulted in making a schematic map showing the total scores for the types of the snow hazard (Fig. 3). As it was not scientifically correct to evaluate the comprehensive snow hazard for the mountainous part of the island based only on two processes out of the number examined (avalanches and snow loads), those regions were excluded from the comparison.

As seen from Fig. 3, the highest total degree of the snow hazard for four processes in question (heavy snowfalls, snowstorms, snow loads, and avalanches) is characteristic of the coastal districts of the island: on the east coast of the Terpeniya Peninsula (Poronaisk district), on the west coast north of Cape Lamanon (Uglegorsk district) and between Cape Slepikovsky and Cape Lopatin (Kholmsk and Nevelsk districts). This is mainly attributed to the combination of a large number of avalanche catchments per 1 km in the coastal avalanche complexes and the long duration of snowstorms on the island coasts.

The schematic map (Fig. 3) also shows the processes which presents the highest danger for the population and the economies of the cities and towns. Analysis of the schematic map demonstrates that the



Municipal formation center	Areal exposure to avalanche hazard, %	Max snow load, kPa	Max duration of snowstorms* per winter, hours	Max amount of snow fell within 12 hours, mm	Volume of stored snow at date of snow patch closure, thousand m^3
Okha	1	4.0	865	27	100
Nogliki	0	4.0	165	27	–
Alexandrovsk-Sakhalinsky	2	4.0	246	18	–
Tymovskoye	0	5.5	36	19	–
Smirnykh	0	3.2	36	19	–
Poronaisk	0	4.0	72	49	100
Shakhtersk	13	4.5	440	30	–
Uglegorsk	13	4.5	440	30	–
Makarov	12	4.8	197	38	100
Tomari	12	4.5	208	25	–
Dolinsk	0	6.0	167	39	200
Kholmsk	29	4.5	636	31	200
Yuzhno-Sakhalinsk	<1	6.0	76	30	1200
Korsakov	4	4.5	95	30	250
Aniva	0	4.8	95	30	–
Nevelsk	45	4.5	472	19	200

Note: dash – no data available.
*Wind velocity exceeding 15 m/s.

Fig. 3. The schematic map of the snow hazard on Sakhalin Island.

Table 2. **Impact of snow-related hazardous processes and phenomena on the population and the economy and the respective protective measures**

Process or phenomenon	Impact on population and economy	Protective measures	
		organizing	engineering
Heavy snowfall	Casualties, stoppage of transport traffic; Need for cleaning of town territories and motor roads; Damage and breakdown of building roofs and windows, of motor vehicles; Massive damage of trees	Stoppage of transport traffic; cancellation of school attendance	Planning of town development considering prevailing winds
Snowstorm			
Anthropogenic snow patch	Development of dangerous exogenous geological processes (flooding, waterlogging, etc.); environmental pollution	–	Well-grounded selection of sites for snow patches; Use of alternative solutions (snow melting plants)
Snow load	Damage and breakdown of roofs of buildings and structures	Timely cleaning of the roofs of buildings and structures	Design and construction of buildings and structures considering the possible amount of snow load; Use of roofs with heat-generating coating
Avalanche	Casualties, damage of buildings, structures, and motor vehicles; Obstruction of territories of settlements and infrastructure facilities	Stoppage of transport traffic; Prohibited access to avalanche-hazardous zones for population; activation of avalanche movement	Construction of snow-retaining structures and/or snow-redistributing structures in the avalanche generation zones; Construction of avalanche-retaining, avalanche-declining, and avalanche-retarding structures (dams, avalanche breakers, anti-avalanche galleries, etc.)

degree of the snow hazard varies in different regions of the island. The highest degree of exposure to avalanches is characteristic of the cities and towns situation on the island coasts (Shakhtersk, Uglegorsk, Kholmsk, Nevelsk, etc.), which is due to the location of the housing territories of these towns directly at the feet of sea terrace slopes, where the length of the avalanche hazardous zone may constitute 80 % of the territorial length.

The maximum values of the snow loads in the territories of the towns vary insignificantly and refer to the high and very high categories of the snow hazard, which is related to the large amount of solid precipitation falling and a lengthy snow cover period.

Snowstorms last longest in the towns of Okha, Uglegorsk, Kholmsk, and Nevelsk. This is related to high wind velocities and to the high occurrence of winds in the coastal areas.

The heaviest snowfalls are characteristic of the southern districts of the island (it is to be reminded that we do not consider the mountainous part of the island in this study, where snowfall intensity may reach much higher values), where the amount of solid precipitation fall per 12 hours may exceed 30 mm, which is due to the trajectories of cyclone passage over the island in the winter season.

The amount of snow stored on the anthropogenic snow patches depends not only on the amount of precipitation falling but also on the area of the city/town to be cleaned, and hence, is not expressly dependent on the meteorological conditions.

Thus, the cities/towns of Okha, Shakhtersk, Uglegorsk, Makarov, Kholmsk, Nevelsk, Yuzhno-Sakhalinsk, Korsakov, and Dolinsk are exposed to the highest degree of the snow hazard. They are situated, with the exception of Okha, Yuzhno-Sakhalinsk, and Dolinsk, on the seashores of the central and southern parts of the island, where the high snow hazard is caused by the negative combination of the hydrometeorological and geomorphological conditions.

About 50 % population of the Sakhalin region live in three cities (Yuzhno-Sakhalinsk, Kholmsk, and Nevelsk), where the snow hazard is estimated at scores 13–16 (maximum values).

Considering the hazardous processes and phenomena related to snow, the following should be pointed out in terms of the damage inflicted by them to the population and the economy of Sakhalin Island: 1) Avalanches cause the greatest number of casualties; 2) Avalanches and snow loads inflict the largest damage and destructions of buildings and structures. Heavy snowfalls and snowstorms, as well as snowdrifts, inflict mainly indirect economic damage, as it is necessary to clean the territories of the settlements, motor roads and railroads from snow. Anthropogenic snow patches cause deterioration of the environmental situation in the adjacent districts and trigger hazardous exogenous geological processes. To reduce the impact of the hazardous processes relating to snow on the population and the economy of the island, a variety of measures have to be taken to protect the population and the facilities (Table 2).

CONCLUSION

In the territory of Sakhalin Island, the highest degree of the snow hazard is characteristic of the fol-

lowing regions of the island: the east coast of the Terpeniya Peninsula (Poronaisk district), the west coast north of Cape Lamanon (Uglegorsk district) and between Cape Slepikovsky and Cape Lopatin (Kholmsk and Nevelsk districts), and the towns of Okha, Shakhtersk, Uglegorsk, Makarov, Kholmsk, Nevelsk, Yuzhno-Sakhalinsk, Korsakov, and Dolinsk.

Generally for Sakhalin Island, the highest degree of the snow hazard is characteristic of coastal territories, which is due to the negative combination of the hydrometeorological and geomorphological conditions, including the long duration of snowstorms, the high intensity of the snowfalls, and the large number of avalanche catchments per 1 km linear length of the shore.

In the regions with a lengthy snow cover period, the problem of the snow hazard of the urbanized territories is quite acute. Currently it is practically impossible to resolve this problem; it is only possible to alleviate the effects of the heavy-snow winters by smarter planning of the town territories, engineering protection and better management.

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