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ORIGINAL PAPER

Debris flow hazards for mountain regions of Russia: regional features and key events

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Abstract The total area of debris flow territories of the Russian Federation accounts for about 10% of the area of the country. The highest debris flow activity areas located in Kamchatka-Kuril, North Caucasus and Baikal debris flow provinces. The largest debris flow events connected with volcano eruptions. Maximum volume of debris flow deposits per one event reached 500×10^6 m^3 (lahar formed during the eruption of Bezymyanny volcano in Kamchatka in 1956). In the mountains of the Greater Caucasus, the maximum volume of transported debris material reached 3×10^6 m^3; the largest debris flows here had glacial reasons. In the Baikal debris flow province, the highest debris flow activity located in the ridges of the Baikal rift zone (the East Sayan Mountains, the Khamar-Daban Ridge and the ridges of the Stanovoye Highland). Spatial features of debris flow processes within the territory of Russia are analyzed, and the map of Debris Flow Hazard in Russia is presented. We classified the debris flow hazard areas into 2 zones, 6 regions and 15 provinces. Warm and cold zones are distinguished. The warm zone covers mountainous areas within the southern part of Russia with temperate climate; rain-induced debris flows are predominant there. The cold zone includes mountainous areas with subarctic and arctic climate; they are characterized by a short warm period, the occurrence of permafrost, as well as the predominance of slush flows. Debris flow events are described for each province. We collected a list of remarkable debris flow events with some parameters of their magnitude and impact. Due to climate change, the characteristics of debris flows will change in the future. Availability of maps and information from previous events will allow to analyze the new cases of debris flows.

Keywords Debris flow · Mudflow · Lahar · Slush flow · Hazard · Russia

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1 Introduction

Debris flows are natural hazards which cause damages and casualties both in Russia and in the other countries of the world (Chernomorets et al. 2007; Hestnes 1998; Hungr et al. 2001; Huggel et al. 2003; Jomelli et al. 2015; Jacob and Hungr 2005; Kadetova et al. 2016; Major and Iverson 1999; Nosov et al. 2006; Petrakov et al. 2007; Revellino et al. 2004; Rickenmann 1999; Perov 2003; Seinova and Zolotarev 2003; Stoffel et al. 2005, 2014; Takahashi 1991; Wei et al. 2010; Hu et al. 2012; Genevois et al. 2001; Vallance and Iverson 2015; Vinogradov 1980; Zaporozhchenko and Kamenyev 2011). The debris flow studies usually deal with local catchments and objects affected by specific flows. The analyses of debris flow features for larger territories are rather few, thus complicating the investigation of debris flow formation trends.

The purpose of this paper is to zone the territory of Russia in terms of debris flow distribution and to characterize specific features of debris flow activity and hazard in different regions of the country, on the basis of results of several decades of debris flow research in the countries of the former USSR. Much of this research has been published only in Russian, and therefore, this paper attempts to review and summarize these results for the English-speaking audience. Total bibliography in Russian includes more than 8100 publications about debris flows in Russia and other countries of former USSR (Vlasov and Krasheninnikova 1969; Vlasov 2008, 2017).

Experts needed the official map of debris flow hazard in USSR for state standards in civil design and development. The published debris flow maps of some regions and districts could not be used for the map of all country, because they covered only small part of mountain areas, and their legends were compiled using different principles. After the decision about the map compilation in 1968, the Institute of Geography, Ministry of Geology, State Hydrometeorological Survey, and other organizations prepared inventoried of debris flow catchments, guidelines on field studies and aerial image interpretation. Methodology of zoning the territory of Russia in terms of debris flow hazard was elaborated at the Laboratory of Snow Avalanches and Debris Flows from Lomonosov Moscow State University (Fleishman and Perov 1976), for the preparation of the map for the territory of all USSR in scale 1: 8,000,000 (Perov and Fleishman 1975). Experts such as B.N. Ivanov, A.N. Oliferov, R.V. Tretyakova, N.V. Dumitrashko, S.S. Korzhuev, V.N. Olyunin, N.L. Kondakova, L.S. Govorukha, D.K. Bashlavin, G.A. Postolenko, O.I. Budarina, T.S. Krayevaya, R.I. Skopintseva participated in preparation of materials for Russian Federation regions. V.F. Perov lead the compilation, and S.M. Fleishman was the scientific editor. These investigations further developed in a number of studies (Perov 1997; Perov et al. 1997, 2007; Perov and Budarina 2000). Versions of the map were published in the official regulations for the design and development (SNiP 2.01.01-82 1983) and atlases (National Atlas of Russia 2008). The map compiled for this paper has been based on those maps with additions and revisions. We prepared the list of main debris flows registered in Russia.

2 Terms and definitions

It is necessary to clarify the definition of a debris flow for the purposes of this paper. According to Hungr et al. (2001), *debris flow* is a very rapid to extremely rapid flow of saturated nonplastic debris in a steep channel. *Mudflow* is a very rapid to extremely rapid flow of saturated plastic debris in a channel, involving significantly greater water content relative to the source material.

Therefore, the difference between terms "debris flow" and "mudflow" is not totally acknowledged. For example, Mudflow = same as debris flow, but more fine-grained debris. Alpine mudflows show the same typical morphology as debris flows, with slide scar at top, erosional gully, block levees and bouldery front lobe, or outspread front fan of finer material. There is no generally accepted Swedish term for debris flow or mudflow (Rapp and Nyberg 1981).

There are some differences in using of terms in Russian and in English. We use the term "debris flow" sensu lato, in the broad sense. In our interpretation, the debris flow in the broad sense is an equivalent of the term "*sel′*" which is traditionally used in Russia. The term *sel′* which includes both debris flow and mud flow is often used in Russia, and the other countries of the former USSR, and also in the Turkic-speaking countries. According to Perov (2003), *sel′* is a flow originating within channels of mountain water streams (temporary or permanent) and consisting of rock debris mixed with water. In this paper, we consider mudflow to be a variety of debris flow.

In other case, the Russian term *opolzen*' ,which is approximate equivalent of "landslide," is generally used sensu stricto. The "sel′" in Russian is not a part of the "opolzen′," while in English both "debris flow" and "mudflow" are types of landslide.

We included the lahars, glacial lake outburst floods (GLOFs), and slush flows into our analysis. These processes fully or partially relate to debris flows and associated phenomena. *Lahar* is an Indonesian term most commonly defined as a rapidly flowing, gravity-driven mixture of rock, debris, and water from a volcano (Vallance and Iverson 2015). *Slush flow* (slushflow) is flowing mixture of water and snow (Hestnes 1998).

The body of a debris flow consists of the debris mass with solid material accounting for 10–75% of its volume (Perov 2012). Its density is 1100–2500 kg/m^3 (Vinogradov 1980; Perov 2014). Debris flows moves at a rate of 2–10 m/s generally. The pulsation (wave) movement, sharp level rise, and rather short duration (mostly 1–3 h) are typical for the debris flows; the average depth of a flow is 2–10 m, while in the channel necks and turns it increases up to 15–20 m (Perov 2012). The volume of transported debris material could reach thousands of cubic meters for small slope debris flows and tens/hundreds of thousands cubic meters in valley debris flow catchments. The maximum amounts are 500×10^3–600×10^3 m^3 in the medium-height mountains (1500–3000 m a.s.l.), and more than 10×10^6 m^3 in the high mountains (over 3000 m a.s.l.).

3 Study area

Russian Federation is located in the northern and northeastern parts of the Eurasia. Area of 17.1 million km^2. The estimated population is 146.5 million people. The plains cover about 65% of the country and are located in the western, central, and eastern parts. Mountain regions are located mainly in the southern, eastern, and southeastern parts of Russia. Mt. Elbrus is the highest point of Russia (5642 m a.s.l.). The level of the Caspian Sea is the lowest point of Russia (-27 m below the ocean level). The highest active volcano is Klyuchevskoy in Kamchatka Peninsula (ca. 4780 m a.s.l.).

The territory of Russia is located in four climatic zones: arctic, subarctic, temperate, and subtropical. Modern glaciers observed in the Arctic islands and in mountainous regions. A general transfer of air masses from west to east is a typical for most of the territory of

Russia. Over the territory of the country are formed and move the arctic, temperate, and tropical air masses. Characterized by a clear seasonal temperature, the presence of long winter (cold) and summer (warm) periods resulting in the frequency of many natural processes. Most of the precipitation falls during the warm season. In winter, the whole country formed a stable snowpack. It exists from 90 to 250 days.

4 Materials and methods

Debris flow processes are widespread in the mountainous areas of Russia and occur to a limited extent within the uplands of plains. The territory of the country is large. Genesis, magnitude, and frequency of debris flows have essential distinctions in different regions. So, the mapping of debris flow activity and hazard was important aim (Perov 2003).

We used the following materials for map compilation:

1. Inventories of catchments where the debris flows have been recorded,
2. Reports about expeditions for debris flow studies.
3. Aerial imagery.
4. Data from publications.
5. Topographic and thematic maps.
6. Dendrochronological studies.

Main works for compilation of debris flow map have been organized in USSR in Soviet period. Several groups of experts participated in these works. Laboratory of Snow Avalanches and Debris Flows, Lomonosov Moscow State University, was a coordination center.

Experts analyzed key gullies and catchments in scale 1:5000–1:25,000. Detailed maps for separate catchments have been compiled after field investigations. These maps contain the information about initiation zones, transition channels, geological structure, and the buildings in impact zones on debris flow fans. After the analysis of catchments, the maps of large basins have been compiled in scale 1: 100,000. These maps included information about debris flow catchments without details. Aerial images used for the mapping.

After the generalization, regional maps have been compiled in scales 1: 200,000–1: 1,000,000. These maps included the location of debris flow gullies and/or catchments, triggers of debris flows, magnitude (maximum volume of deposits per one event). As a rule, the inventories of debris flow catchments were made in complex with maps for regions. Examples of the maps of same territory in different scales are presented in Fig. 1.

Regional maps were sources for compilation of map for all the USSR. For the mapping of all USSR, we compiled maps of separate factors of debris flow formation (relief, climate, anthropogenic activity, etc.) (Perov 2012). Then, the level of debris flow activity assessed, and borders of debris flow regions mapped using developed criteria. The relative density of debris flow channels was the important characteristic. We calculated the relative density of channels as a result of division of number of debris flow channels to the total number of all channels in the area.

Under the first stage of investigation, the Map of Debris Flow Areas in the USSR at a scale 1: 8,000,000 was compiled through generalization and systematization of available information (Perov and Fleishman 1975). Since the data on parameters and regime were scarce, the assessment of activity level was accomplished using indirect methods, in particular, taking account of relative mountain altitude.

Additional criteria were the frequency and the volume of deposits per event. Potentially, hazardous regions also were identified (Table 1).

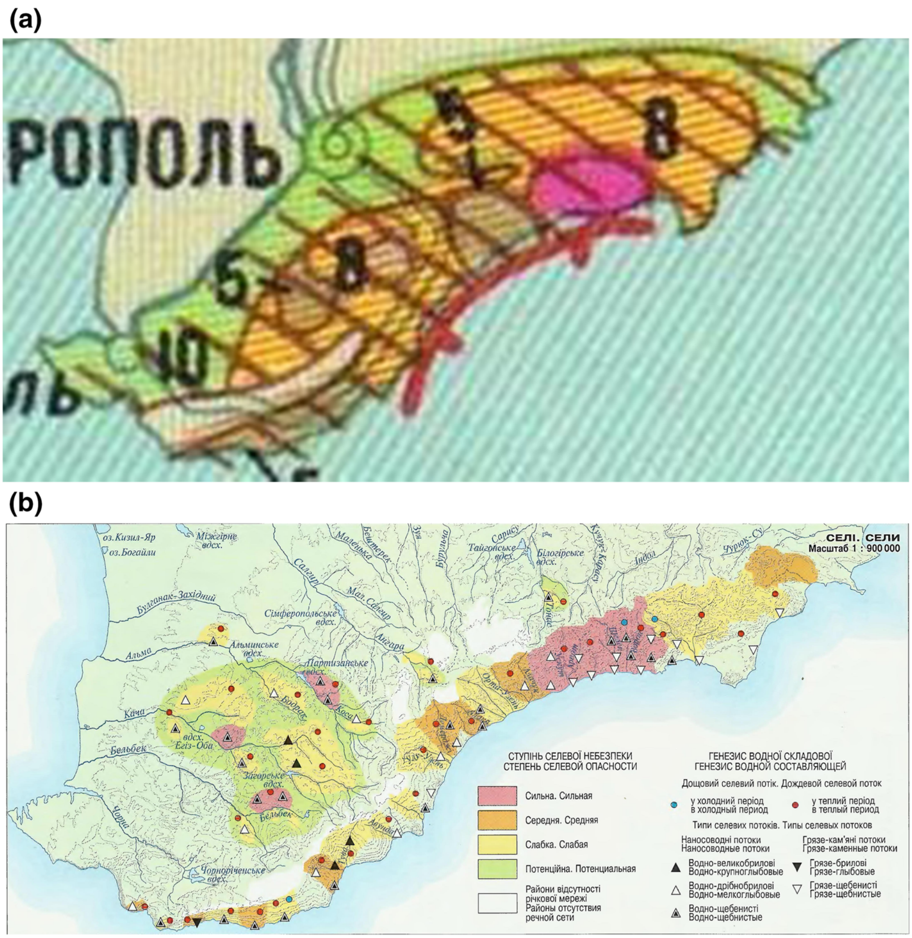

Fig. 1 Examples of the debris flow maps of the same territory compiled in different scales: **a** 1: 8,000,000 (Perov and Fleishman 1975); **b** 1: 900,000 (The Autonomous Republic of Crimea, Atlas 2004)

If the records of events were poor, the following information took in account as favorable for the debris flow activity: slope >0.1; thick layers of unconsolidated Quaternary deposits, high seismicity, large amount, and frequency of maximum daily rain precipitation, presence of glaciers and volcanoes, high level of anthropogenic activity.

Genesis of water component have used for mapping: rain-induced, snow-melting, glacial, and mixed types. Also, specific types of debris flows included into map: volcano-induced debris flows (lahars) and seismically triggered debris flows. The areas of flows similar to debris flows, including slush flows in polar regions, and debris floods in arid regions, have been also investigated and mapped.

Characteristics of genesis were based on the genetic classification of mudflow phenomena (Perov 1996). This map depicts prevailing genetic types of debris flows occurring separately and in combinations. Two main characteristics (activity level and genesis) have been combined in the map. The compilation of the map involved such methods as field investigations of the representative key areas, aerial imagery interpretation, and analysis of

Table 1 Assessment of debris flow hazard for territories

Criteria		Level of debris flow hazard			
		High	Middle	Low	Potential
Main	Density of debris flow gullies	Amount of debris flow channels is larger than amount of channels without debris flows	Amount of debris flow channels is lesser than amount of channels without debris flows	Debris flow channels are located sporadically	No traces of debris flows, but it is possible to activate debris flows if natural balance will be violated
Additional	Frequency of debris flows	<3–5 years	6–15 years	>15 years	
	Volumes of debris flow deposits per one event	>100,000 m^3	10,000–100,000 m^3	<10,000 m^3	

factors of debris flow formation (climatic, geomorphological, lithological factors, soils, and vegetation, anthropogenic activity).

After publishing of the first version of the map in 1975, the Laboratory of Snow Avalanches and Debris Flows, MSU during a few decades organized expeditions to different regions of Russia for additional study of areas for which information was incomplete. Dendrogeomorphological studies covered selected mountain territory of Russia. Experts took and analyzed samples (more than 1000 samples in total) for tree ring analysis in key catchments in the following regions: Central Caucasus (Kabardino-Balkariya and Karachay-Cherkessia republics), Khibiny Mts., Stanovoye Highland (Chara-Tokka basin, Udokan ridge), Kamchatka Peninsula (Mutnovsky, Avachinsky, Shiveluch, Klyuchevskoy volcanoes), Sakhalin Island, Putorana Mts (Lake Lama basin), Magadan region (mountains near the western coast of the Sea of Okhotsk). Dendrogeomorphological data have been used for dating of debris flow events of latest 10–100 years, making it possible to form the conclusions on their frequency. After additional studies in poorly investigated regions, the new versions of the map were compiled (Perov 1989; Perov and Budarina 2000; National Atlas of Russia 2008).

Since the new data have been received during recent research of debris flows in volcanic and glacierized areas of Russia (Chernomorets and Seynova 2010; Seynova et al. 2014; Dokukin et al. 2016; Salaorni et al. 2017), we included the results of satellite imagery interpretation into this paper. In particular, we included all volcanoes erupted in 20–21 centuries from our database of lahars of Russia into the new map. Also, we edited some map polygons using new field data and governmental information.

5 Results

As a result, we present the map and the information about the distribution, activity, and the remarkable debris flow events.

Debris flow hierarchical zonation has been developed in (Perov and Budarina 2000). It includes two debris flow zones (warm and cold) in accordance with the prevailing water component of debris flows: precipitation of liquid water and melting of snow/ice. Zones have been divided to 6 debris flow regions and 15 debris flow provinces. The debris flow zones, regions, and provinces are briefly described in Table 2. Duration and main periods of debris flow activity in the regions are summarized in this table.

We present a simplified map of the Debris Flow Hazardous Areas in Russia (Fig. 2). Because of its scale, the map does not show anthropogenic debris flows which have a small extension. High reliability of the map is confirmed by the records of recent debris flow events.

5.1 Warm zone

A. **European region** includes three provinces—North Caucasus, South Urals, and Crimea.

1. **North Caucasus debris flow province** covers the mountains of the Greater Caucasus within the territory of Russia. The mountainous areas of the Krasnodar and Stavropol territories, and the republics of Adygeya, Kabardino-Balkariya, North Ossetia-Alaniya, Ingushetiya, Chechnya, and Dagestan are included in the province.

The Greater Caucasus has three parts, i.e., Western, Central and East. The Central Caucasus lies between the Elbrus (the most prominent peak in Europe—5642 m) and Kazbek (5033 m) mountains. The Caucasus is the high-mountain area with the Alpine-type relief and glaciation (about 850 km^2 in the Russian part). The prevailing absolute elevations of ranges are 2000–4000 m, and relative altitudes are about 1000–1500 m. Ranges in the axial part of the Central and Western Caucasus are mainly built of metamorphic slates, gneisses and granites. Limestones, marl, sandstones, and clay slates prevail in the Front

Table 2 Zoning of debris flow hazardous areas of Russia

Zones	Regions	Provinces	Season of debris flow activity, months[a]
I. Warm	A. European	1. North Caucasus	January–December
		2. South Urals	May–December
		3. Crimea	January–December
	B. South Siberian	4. Altai	April–August
		5. Baikal	May–August
	C. Pacific	6. Amur	April–September
		7. Sakhalin	June–October
		8. Kamchatka–Kuril	June–October[b]
II. Cold	D. West	9. Kola	May–August
		10. Polar Urals	May–August
	E. East	11. Putorana	May–August
		12. Verkhoyansk	May–August
		13. Kolyma-Chukchi	May–August
	F. Arctic	14. Taymyr	June–August
		15. Polar Insular	June–August

Debris flow regime

[a] Unique debris flow events caused by extreme conditions are possible beyond the dates of the debris flow season

[b] Volcanogenic debris flows (lahars) could occur throughout the year

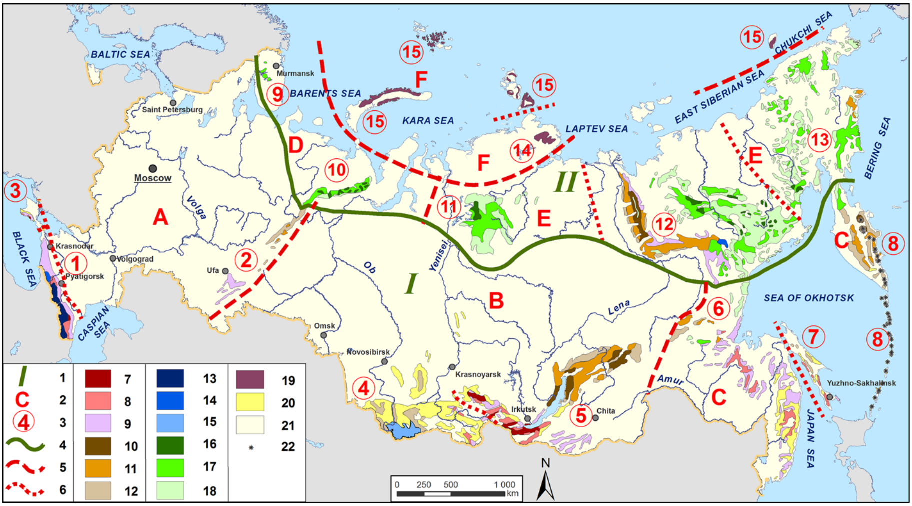

Fig. 2 Debris flow hazardous areas in Russia. Zoning of debris flow hazard territories. Indices: *1*—zones, *2*—regions, *3*—provinces. Boundaries: *4*—zones, *5*—regions, *6*—provinces (see Table 2 for province names). Types of debris flows and degree of debris flow activity: rain-induced debris flows (*7*—high, *8*—medium, *9*—low activity); rain-induced debris flows (predominant) and slush flows (*10*—high, *11*—medium, *12*—low activity); rain-induced (predominant) and glacial debris flows (*13*—high, *14*—medium, *15*—low activity); slush flows and rain-induced debris flows (*16*—high, *17*—medium, *18*—low activity); *19*—slush flows; *20*—territories with potential debris flow activity; *21*—territories without debris flows, *22*—active volcanoes with lahars

Range and the axial part of the East Caucasus. West to east the climate changes from humid to dry. The annual precipitation is 2500 mm in the Western Caucasus, 1500 mm in the Central Caucasus and 1000 mm in the East Caucasus. Besides glacial and nival landscapes, mountain meadows, mountain forests, and mountain steppe occur there.

The North Caucasus is the most active region of Russia in terms of the debris flow intensity. Debris flow processes in the region are well studied. The research started in the middle of the nineteenth century (Statkowski 1879). The available data were integrated in a number of significant studies (Khmaladze 1969; Fleishman and Perov 1976; Zalikhanov 2001; Nosov et al. 2006; Seinova and Zolotarev 2003). Almost all mountainous areas of the North Caucasus are prone to debris flow hazard. The highest debris flow activity is typical for the Central Caucasus Mountains (Seinova et al. 2007). In the East Caucasus, the glaciation retreated during last decades. Precipitation is relatively small here, but the intensity of debris flow activity is high. The Western Caucasus is considerably lower and covered with forests. It is the least active in terms of the debris flow intensity; the density of debris flow channel network and the amounts of debris transported by the flows sharply decrease there as well. Rain-induced debris flows are predominant over the North Caucasus while the glacial debris flows accompany them in the axial, glacier dominated zone of the range. Slush flows are rather occasional.

The volume of material transported by debris flows in the Central Caucasus is typically dozens of thousands m^3. Catchments with the volume of transported debris above 100×10^3 m^3 account for about 10% of the total number of events. Medium and small debris flows (1×10^3–100×10^3 m^3 of transported debris) are widespread in the East Caucasus; debris flow catchments with the volume of transported debris above 100×10^3 m^3 account for less than 5% of the total number. Small debris flows, which transport thousands of m^3 of debris material, prevail in the Western Caucasus; catchments with the volume of transported debris above 10 thousand m^3 account for about 5% of the total number.

Large debris flows are of glacial origin. On August 1–3, 1940, debris flow from the Dzhalovchat gorge in the Adyrsu River valley (Kabardino-Balkaria) transported about 3×10^6 m^3 of debris material; two mountaineering camps were destroyed. On July 19, 1983, the debris flow destroyed the Dzhaylyk mountaineering camp in the same valley (Zaporozhchenko 1985; Bozhinskiy et al. 2008; Zaporozhchenko and Kamenyev 2011).

On July 18–25, 2000, a series of debris flows on the Gerkhozhan-Su River (the Baksan River catchment, Kabardino-Balkaria) resulted in the accumulation of about 2.1×10^6 m^3 of debris material; the Baksan River was dammed and the town of Tyrnyauz was partly flooded. Eight people were lost, and significant damage was caused to the economy of the city and its industrial enterprises (Petrakov et al. 2004, Seynova et al. 2011) (Fig. 3).

Fig. 3 Effects of a glacier debris flow on the Gerkhozhan-Su River in July 2000: **a** West Kayaarty canyon formed by debris flows. *Photo* A.A. Aleynikov, **b** destroyed residential quarter in the town of Tyrnyauz. *Photo* S.S. Chernomorets

The glacial lake outburst floods (GLOF) sometimes occur in this region. The Bashkara Lake outburst in 1958 and 1959, lakes near the Birdzhalychiran Glacier in 1909 and 2006, and the Azau Lake in 1978 and 2011 (Chernomorets et al. 2007; Petrakov et al. 2007, 2012; Dokukin and Shagin 2014; Dokukin and Khatkutov 2016).

In 1974, a glacial debris flow on the Temir River (the Avarian Koysu River catchment in Dagestan) transported about 1×10^6 m^3 of debris material. The maximum volume of debris material transported by a rain-induced debris flow was about 0.25×10^6 m^3 (the Intitlyar River, other tributary of the Avarian Koysu, June 1972). Both debris flow events resulted in the temporary damming of the Avarian Koysu River.

Rather occasional glacial disasters characterized by enormous volumes of removed ice and debris and cause catastrophic consequences. Such events called Kolka/Karmadon disaster occurred in the Genaldon River (North Ossetia). On July 3, 1902, the flow transported more than 70×10^6 m^3 of ice, rocks, water, and claimed the lives of 32 people (Chernomorets and Adtseev 2014). On September 20, 2002, an ice-rock avalanche formed in this gorge which later transformed into a debris flow. The volume of transported material was about 115×10^6 m^3; 125 people were lost (Haeberli et al. 2004; Chernomorets 2005; Tutubalina et al. 2005; Petrakov et al. 2008; Evans et al. 2009). This is the largest documented glacial disaster in the North Caucasus (Chernomorets et al. 2007).

If we take into account occasional events, the debris flow hazardous period lasts for the whole year in the North Caucasus. More than 90% of debris flows are recorded during May to September; July–August is the most hazardous period (72% of events). The average frequency of rain-induced debris flows is once every 8 years. Two characteristic types of debris flow catchments, with average frequencies of one event per 3–5 years and one event per 10–12 years, are characteristic of the Central Caucasus Mountains. The first type includes small catchments with the origination zones within the Alpine belt, within the areas of sandy-argillaceous rocks. The second type includes larger catchments with the origination zones in the subnival belt, within the areas of crystalline rocks and ancient moraines.

Debris flows of glacial origin occur in July–August. These flows are characterized by the alternation of dormant periods lasting for 15–20 years with the periods of activity lasting for 3–4 years.

Numerous debris flows were recorded in the Central Caucasus in 1953, 1967, 1983, 2002, 2011, 2014, and in 1963 in the East Caucasus (Seinova and Zolotarev 2003; Dokukin et al. 2013, 2016). In July 2011, one of the debris flows transported large boulders up to 13 m in size from the Gyulchi-Su River gorge (Fig. 4).

Occurrence of debris flow processes by man-made activities is the most obvious in the areas of mining industry. The dumps of quarries and mines become the triggering sources of anthropogenic debris flows or increase the volume of material transported by natural events (vicinities of Novorossiysk and Tyrnyauz towns, the settlement of Sadon, the village of Zayukovo). Overgrazing by cattle on the slopes often increases the erosion and formation of small debris flows near the settlements.

Debris flows in the North Caucasus damage mainly roads, towns and settlements, and recreation facilities. The towns of Novorossiysk and Tuapse, other settlements, and the majority of mountain highways are built in debris flow prone areas (Shnyparkov et al. 2013; Baburin et al. 2014). The debris flow control measures are rather limited in their scope (Zarudnev et al. 2007). The risk of debris flows is partly counter-balanced by construction of check dams and by planting shrubs in the vicinity of Novorossiysk and by construction of a debris flow channel in the town of Tyrnyauz. Before the 2014 Olympic Games, flexible barriers were installed in the catchment of the Mzymta River (Barinov

Fig. 4 Boulders transported by a debris flow down the Gyulchi-Su River (Caucasus) in July 2011. *Photo* S.S. Chernomorets

2013). The majority of economic facilities which are exposed to debris flow impacts are not protected; and there are practically no examples of land reclamation with natural plants.

2. **South Urals debris flow province** covers the Northern, Central, and Southern Urals. Parts of the Perm Territory, the Chelyabinsk and Orenburg regions, and the Republic of Bashkortostan are included in the province. The absolute elevations of ranges are 700–900 m, and the relative altitudes are 400–700 m.

Mountains are built of metamorphic, effusive, and intrusive complexes of rocks. The mountain taiga landscapes prevail in the north and steppes in the south. Natural conditions are unfavorable for debris flows formation; occasional rain-induced debris flows are possible in the axial (upper) zone of ranges. However, long industrial and agricultural development, as well as the deforestation, have resulted in the intensification of erosion and debris flow processes in the Central and Southern Urals. The recorded debris flows were caused by heavy rains within the areas of disturbed or transformed landscapes; thus they were of anthropogenic or natural-anthropogenic origin.

Fans of debris flows are present in the upper courses of the Yuryuzan River, near the towns of Beloretsk, Zlatoust, Ust-Katav, Katav-Ivanovsk, and in the Kroka and Revdinsky massifs (Fleishman and Perov 1976). On July 17, 1966, a shower rain which provided 67 mm/day of rainfall caused a debris flow which demolished bridges and flooded factory buildings (Kherkheulidze 1967).

Predominately, anthropogenic character of debris flow processes in the region is confirmed by their expansion on the foothill plains. A debris flow near the town of Perm was formed because the vegetation was destroyed by the gaseous emissions of concentrating mills and chemical plants. On June 24, 1979, after the hailstorm, a debris flow was formed on the tilled slope of the Tuzlukkol stream, the left tributary of the Ural River (Goryainov 1988). The flow demolished a permanent bridge, soils were washed away and more than 1300 hectares of crops were buried under sediments.

In the northernmost part of the Northern Urals, slush flows occur as well as the rain-induced debris flows. The largest ones are formed during the spring snowmelt. One of them was recorded in May, 1954, in the upper courses of the Shchugor River (Kemmerikh 1961).

3. **Crimea debris flow province**.

Elevations of the Crimean Mountains are 700–1200 m, and the depth of dissection is up to 800 m. They are mainly built of flysch and limestone. Slopes and flat tops of the mountains are covered with sparse forests of beech, pine and oak, and also with shrubs and steppe communities. The annual precipitation is 500–1200 mm; the daily maxima of 1% occurrence are 75–150 mm.

The first record of debris flow event in Crimea, near the town of Alushta, dates back to 1899 (Klepinin 1937). The data about formation conditions, parameters of debris flow catchments, and debris flows themselves are reviewed by Klyukin (2007) and Oliferov (2007). The distribution and degree of the debris flow hazard are shown in the small-scale maps (Aizenberg et al. 1965).

Mud floods and water–rock flows are characteristic of the Crimean Mountains. The debris flows are mostly rain-induced and of the erosional origin.

The debris flows could occur throughout the year; 90% of events happen during the summer (June–August) and 10% in winter and spring. The frequency of debris flows is average (one event in 10–15 years within the southeast area) and occasional (one event in 50–100 years in the northern foothills). Small debris flows (transporting <10,000 m^3) and medium-scale events (10,000–100,000 m^3) are the most common. Larger debris flows (100,000–1,000,000 m^3), such as on the Uchan Su River, are quite few and far between (Oliferov 2007).

The largest and most numerous debris flow events occurred in 1948, 1949, 1956, 1968 and 1997. On August 12, 1997, a debris flow was formed in the Demerdzhi River during a storm which provided 85 mm of rainfall (Oliferov 2007). Its discharge amounted to 146 m^3/s, the river channel became 0.5–1.5 m deeper, and the total volume of transported material was about 30 thousand m^3 (Perov 2012).

In July, 1967, the Kutlak River debris flow took away a bus with local people near the Veseloye village. 20 people, including 15 children, died (Oliferov 2008).

Debris flows become more active due to consequences of economic activities, i.e., deforestation and degradation of soil and vegetation as a result of overgrazing. This trend was recorded since mid-nineteenth century. Some debris flows were formed after the failures of poorly constructed earth dams.

In general, the debris flow phenomena in the mountainous part of Crimea are not large. However, vineyards and gardens, settlements and individual constructions, and highways are affected. Measures such as construction of debris flow drainage canals, sediment control and regulation, and construction of bank protection walls are used to control the debris flows. In the 1950s, mechanized terracing of eroded slopes in combination with forest plantation was introduced, which proved to be effective under the natural conditions of Crimea.

B. **South Siberian region** includes the Altai and Baikal debris flow provinces.

4. **Altai debris flow province** includes the Altai Mountains, Western Sayan Mountains, Gornaya Shoriya, Salair Range, and Kuznetsk Alatau. It covers the territory of the Altai Territory, the Kemerovo Region, the Republics of Altai, Khakassia, and Tyva. The Altai Mountains are well studied in terms of the debris flow phenomena (Vinogradov et al.

1987). Average absolute elevations of its ranges are 1000–3500 m, and relative altitudes vary from 400 to 1400 m. The mid-mountain relief and the mountain taiga landscapes are typical for these areas. The annual precipitation is up to 1500–2000 mm in the west and northwest, and 100–300 mm in the southeast; 76–90% of the annual total precipitation falls during the warm season (April–October); the monthly maxima are most often in July–August.

All larger debris flows in the Altai Mountains, and the most of small ones are rain-induced. The largest debris flows formed near the Teletskoye Lake. They occurred after daily precipitation of 55–70 mm. Large debris flow events were recorded on July 10–11, 1963, and on July 21, 1970. The 1963 debris flow was formed in the night of July 11 on the Bayas River, the left tributary of the Kyga River. The debris flow originated on the forest area after the wildfire in 1962. The volume of transported material was about 500 thousand m^3. The 1970 debris flow was formed on the tributary of the Kyga River as a result of the collapse of landslide dams. The volume of transported material was about 60,000 m^3.

Occasional debris flows are also formed as a result of the glacial lake outbursts. In July 2012, Lake Maashey, which was about 1.5 km long, outburst and disappeared after nearly 100 years of existence (Rudoy et al. 2012).

The hazardous period of rain-induced debris flows lasts from April to August, and the period of the highest activity is June–July. If occasional slush flows are considered, the beginning of the debris flow period should be moved to February.

The erosion and debris flow processes slightly increase as a result of economic activities, such as deforestation, overgrazing, and construction works. Open pasture slopes are covered with a network of erosion channels. The recent channels are 2.0–3.6 km long on the right bank of the Katun and Ursul rivers (Vinogradov 1976, 1978).

The areas with low and potential debris flow hazard prevail within the Altai debris flow province. Limited areas of average hazard are identified near the Teletskoye Lake (Korbu and Chulyshmansky ridges) and in the south, on the Katunsky, Southern Chuya, and Northern Chuya ridges. Rather poor development of debris flow processes is mainly due to the stepped structure of terrain, domination of mountain taiga landscapes, and low precipitation in the inner (southeast) regions of the Altai Mountains.

5. **Baikal debris flow province** covers mountain systems of the East Sayan Mountains, Khamar-Daban, Stanovoy Highland, and other smaller mountains. It includes parts of the Irkutsk Region, the Zabaykalsky Territory, the Republics of Buryatia, and Sakha (Yakutia).

Absolute elevation of ridges reaches 3491 m. Metamorphic rocks and granites are predominant. The territory has continental climate and mountain taiga mid-mountain landscapes. The debris flows originate mainly because of heavy rains, sometimes accompanied by snowmelt processes. Numerous debris flows are formed after steady rains culminating in a shower rain. Solid component of debris flows is provided by the processes of weathering. The outbreak of temporary dams formed by rock slides is of particular importance for debris flow origination. Some dams appeared just before the debris flow events as a result of heavy rains, and others were formed long ago. The volume of temporarily dammed lakes could be 10–250 thousand m^3 (Drobot 1983). The trunks are characteristic component of both the dams and the debris flow deposits.

According to the regime hydrometeorological observations in the East Sayan Mountains, channel accumulation of loose deposits sufficient for a debris flow formation requires 4–5 years (Laperdin and Trzcinski 1976). Debris flows are of water–rock type. The maximum volume of transported material is 300–590 thousand m^3. The debris flow period lasts from June until August, most events occur in the end of June and July. At the beginning of summer, the formation of debris flows is limited to the lower mountain belts;

floods and low-density debris flows in large catchments are characteristic of this period. In the second half of summer, after the thawing of long-term and seasonal permafrost on the rocky mountain summits, the process expands over the whole mountainous area, resulting in water–rock and mud-rock debris flows. According to dendrochronological data, the frequency of large debris flows is once every 16–30 years, and small ones occur once every 4–8 years.

Destructive debris flows were recorded in 2014 near the settlement of Arshan (Makarov et al. 2014; Kadetova et al. 2016). Nine houses were demolished, 52 buildings were covered with silt, an automobile bridge was destroyed, and one person died. The debris flow deposits in second Shikhtolayka gully presented on Fig. 5.

The Khamar-Daban Ridge is located along the southern shore of the Baikal Lake. The rainstorm debris flows prevail there. During the period of high debris flow activity in 1971, the daily maxima of precipitation were 100–260 mm. Almost all catchments less than 150–200 km^2 on the northern slope of the Khamar-Daban Ridge are active in terms of debris flow formation; catchments less than 100 km^2 are the most active. Water–rock debris flows are typical for the western part of the ridge and mud-rock debris flows are

Fig. 5 The 2014 debris flows in Arshan village (East Siberia, Republic of Buryatia). Debris flow origination site and deposits of second Shikhtolayka gully (*left* image), the building after the debris flow deposits 6–8 m in thickness was evacuated. *Photo* Sergey Chernomorets

predominant in its eastern part with clay deposits at the foothills. Volumes of large debris flows amount to 300–500 thousand m^3 and more. As a result of numerous debris flows on the southern shore of the Baikal Lake in 1962 and 1971, over 3×10^6 m^3 and about 5×10^6–8×10^6 m^3 of debris material, respectively, were transported to the lake. The Circum-Baikal segment of the East Siberian Railway, the highway, industrial, and residential buildings and farmlands are affected by debris flows. The debris flows on the Slyudyanka River caused damage in 1915, 1934, and 1960. The last event resulted in the destruction of 15 and damage of 50 houses (Solonenko 1963). Debris flow control constructions, such as single-span bridges, are built to protect railroads and highways; the settlements are protected with dams.

The Stanovoye Highlands is a system of medium-elevation mountains and wide rift valleys between the northernmost tip of the Baikal Lake and the Olyokma River. Like the other parts of the Baikal rift zone, the highland is marked by a block structure, contrasting relief, active neotectonic, and recent tectonic processes and high seismic activity. Debris flow processes are well represented within the Stanovoye Highland. The main genetic type of debris flows are rain-induced ones. Rain debris flows are formed in the second half of the summer owing to heavy rains or steady rains culminating in a shower rain. The large rain-induced debris flows affecting several catchments at the same time were recorded in July, 1956, in the Kalar Ridge, in July, 1958, and in August, 1977, in the Kodar Ridge, in July, 1967, and in August, 1983, in the Udokan Ridge. In spring and the beginning of summer, melting snow also contributes to debris flow formation. This gives birth to slush flows composed of snow, ice, and water with rock fragments. Slush flows occurred in June, 1971, in the Udokan Ridge, in June, 1976, in the Kodar Ridge, and in May, 1982, in the Baikal Mountains.

Debris flow processes are activated by strong earthquakes, which induced many rock falls and rock slides. After the Muya earthquake (June 27, 1957; magnitude 7.6), the new screes and collapses covered the area of about 150 thousand km^2, 350 km from the epicenter (Tatevossian et al. 2010). Seismically triggered rock avalanches in the Kodar Ridge are also related to this earthquake. According to dendrochronological data, the 1957 debris flows occurred in the Muyakan, Kalar, Kodar and Udokan ridges. The debris flow activity of 1958 was stimulated by the ongoing cleaning of valleys from the debris material dumped by the 1957 earthquake.

Small debris flow catchments (3–6, up to 10 km^2) are prevalent within the Stanovoye Highlands. The frequency of debris flows is once every 3–6 years, and they are of mud-rock, water–rock and slush types. The catchments of 15–60 km^2 produce the maximum volumes of transported debris of about 100–300 thousand m^3, the frequency of debris flows is once every 10–20 years, and these are mainly water–rock flows. The largest debris flow catchments (up to 100–120 km^2) are characterized by mountain mud floods. Tree trunks and fragments often account for a considerable share of the debris material. The debris flow period lasts from May to August; in May–June slush flows and rain-induced debris flows are formed, while the rain debris flows are the most typical for July–August.

Due to the active economic development of the area the problems of anthropogenic debris flows, damage and protection grow in importance. In the 1970s, the assessment of debris flow hazard was carried out prior to the construction of the Baikal-Amur Mainline railway (BAM) (Perov et al. 1984). Constructions for debris flow control were built; however, in some cases, the protection was insufficient. For example, in 2002, as a result of 140 mm of rainfall a debris flow, moving at a speed of 10–15 m/s, reached the railroad near the Bolshoye Leprindo Lake (Lukashov 2008).

In August, 1987, a rainstorm debris flow in the Udokan Ridge was triggered by the washout of a temporary dam in a stream channel (the dam was, created by a road leading to a geological exploration tunnel). Seven road bridges and 3 km of the roadbed were destroyed (Perov et al. 1984). To prevent the expansion of debris flow processes in the region, it is vital to protect forests on mountain slopes and at their foothills.

C. **Pacific region**: Amur, Sakhalin, and Kamchatka-Kuril debris flow provinces.

6. The **Amur debris flow province** covers the Stanovoy Ridge, the Dzhugdzhur and the Sikhote-Alin Mountains, and also lesser ridges and massifs of the Amur River catchment and the Aldan Highland. In terms of administrative districts, it includes parts of the Khabarovsk Territory and Primorsky Kray, the Amur Region and the Republic of Sakha (Yakutia). The prevailing absolute elevations of ridges vary between 1000 and 2000 m, and the relative altitudes are 500–1000 m. Mountains are built of gneisses, granites, and volcanic rocks in the north, and volcanogenic and sedimentary rocks (conglomerates, sandstones, aleurolites, and argillites) in the south. The dominating landscapes are mountain taiga and mountain tundra.

The debris flow phenomena are widespread practically in all ridges; they are the most active in the axial and uppermost parts. The debris flow catchments are located within the areas of ancient glaciation and the zones of tectonic faults. Distinct signs of debris flow processes, such as valley debris flows, were recorded in the ridges of Tokinsky Stanovik, Tylsky, Taykansky, Selemzhinsky, Yam-Alin, Aesop, Dusse-Alin, Bureinsky and Badzhalsky, and in the Dzhugdzhur Mountains. Rain-induced debris flows are the dominating genetic type, while slush flows are wider spread in the northern parts of the province.

In the Sikhote-Alin Ridge the debris flow phenomena are confined to local near-watershed areas; the most part of the mountains is characterized by only potential debris flow hazard. Slope and small-channel catchments prevail. According to single dendrochronological data from the Kema River catchment, the frequency of debris flows is one event per 9 years (Glubokov 1982). Our field investigations proved that mountain mud floods and slush flows occur on the northern slope of the Tokinsky Stanovik Ridge. According to dendrochronological data, the average frequency of slush flows is one event per 6 years. Judging by the evidence in the transit zone the parameters of flows are as follows: depth from 2 to 7 m (up to 10 m on the turns), and width from 10 to 25 m. The maximum size of transported boulders is 1–2 m. The debris flow processes become more intense in the areas of economic development. Small slope debris flows were recorded within the areas of forest cutting and construction works. Preservation of mountain forests would contribute to controlling the debris flow processes.

7**. Sakhalin debris flow province** covers the Sakhalin Island territory.

Ridges of the Sakhalin Island have average absolute elevations of 600–1200 m and relative altitudes of 400–600 m. They are built of sandy-argillaceous rocks which are rather easily weathered. Climate of the island is humid monsoonal; and taiga landscapes of medium-height mountains are predominant.

Two groups of debris flow hazard areas, i.e., the coastal zone and ridges themselves, could be distinguished within the island (Budarina et al. 1987). The coastal zone areas are most active in terms of debris flows and have an average degree of debris flow hazard. Within the ridges the debris flow phenomena are occasional; the degree of hazard is low or just potential there. Debris flows of the coastal zone are formed in short gully-like valleys which dissect high sea terraces, and less often in longer (3–6 km) valleys rising from the slopes of coastal ridges. The majority of debris flows are of rain genesis. Occasional slush flow events were also recorded. Formation of debris flows in the southern part of the island was intensified by forest cutting. Plentiful rainfall is mainly due to the deep cyclones passing over the island. The debris flow period lasts from June to October, and the period of the highest hazard is August–September. The average frequency of rain-induced debris flows is one event per 3–5 years. Multiple debris flows from the dozens of debris flow catchments were recorded in 1971, 1981, and 1994. They were triggered by the typhoons producing multi-day rains (up to 200 mm per day).

The characteristic volumes of debris flows are 2–5 thousand m^3, and the maxima reach 300 thousand m^3. However, they cause a plural damage (Gensiorovsky and Kazakov 2009). Principal objects of destructions are motor and rail roads, bridges, and houses. The greatest damage was caused by a mass debris flows occurrence in August, 1981. Several kilometers of the roadbed, communication and power transmission lines were destroyed; some dozens of houses were damaged. As a result of debris flows in September, 1992, communication between the southern and central parts of the island was interrupted for 2 weeks.

At present, new pipelines are under construction on the Sakhalin Island and a number of their sites are subject to debris flow hazard.

8. **Kamchatka-Kuril debris flow province** includes mountainous areas of the Kamchatka Peninsula and the Kuril Islands (the Kamchatka Territory and the part of the Sakhalin Region).

Rain-induced debris flows, slush flows, and lahars are widespread in Kamchatka; the latter are the specific debris flow processes of the province. Volcano-induced debris flows (lahars) are formed within the Vostochny Ridge where the active volcanoes are localized. The mechanism of lahars formation after the explosive eruption of volcanoes is the instant melting of snow over a vast area under the influence of burning-hot pyroclastic flows. Within 1–2 years after the pyroclastic material completely covered the former course, the river incises to the depth of 8–15 m (Seynova et al. 2014) (Fig. 6).

Less often the active snow and ice melting could be caused by lava flows (Seynova et al. 2010; Belousov et al. 2011). The huge mass of water involves the abundant friable material from the volcano slopes, forming a mudflow. The routes of volcano-induced debris flows are usually 15–20 km long, and they transport hundreds of thousands cubic meters of debris material. The investigations (Bazanova et al. 2001; Belousov 1994; Chernomorets and Seynova 2010) and the results of our expeditions proved that volcano-induced debris flows accompanied the eruptions of the Avacha Volcano in 1926, 1938, the Koryak Volcano in 2009, the Klyuchevskoy Volcano in 1932, 1938, 1945, 1978–1980, 1985, 1988, 1994, 2005, 2007, 2008 and in other years, the Bezymyanny Volcano in 1956, 1961, 1965, 1997, and the Shiveluch Volcano in 1854, 1964, 1993, 2001, 2002, 2004, 2005, 2007, 2009, 2011, 2012, 2015.

The largest flow was formed as a result of the direct blast of the Bezymyanny Volcano on March 30, 1956 (Gorshkov 1959). The hot pyroclastic material was deposited over the area of about 500 km^2. The debris flow covered a distance of 85 km to the mouth of the Bolshaya Khapitsa River, having totally transformed the terrain of the valley. The deposits, mainly sand and silt, were on average 1–2 m thick, the maximum being about 20 m. The total amount of transported hot debris masses was about 500×10^6 m^3 (the absolute maximum for all types of debris flows in Russia). The lahar destroyed the forests and caused mass death of fish in the Kamchatka River; and for a week, its water was unsuitable for use because of high turbidity. Later on the canyons which were cut through in pyroclastic and landslide deposits became ways of new lahars (Fig. 6b). In that way, large lahars were formed after the 1997 eruption (Belousov et al. 2002).

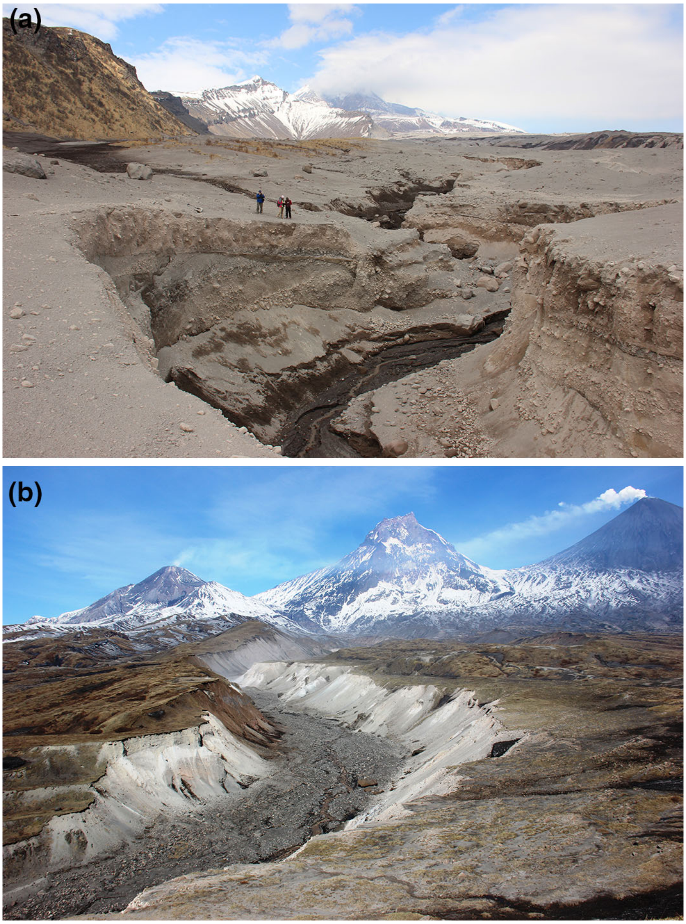

Fig. 6 Lahars on volcanoes in Kamchatka Peninsula. The formation mechanism is the deep erosion of pyroclastic sediments during heavy rains and snowmelt. **a** The Baydarnaya River valley, Shiveluch Volcano. **b** Paths of the largest lahar in the history of Russia formed by the Bezymyanny Volcano eruption in 1956. The Sukhaya Khapitsa River. In the background from *left* to *right*: The Bezymyanny Volcano (active), the Kamen Volcano (extinct), and the Klyuchevskoy Volcano (active). *Photo* S.S. Chernomorets

Rain-induced debris flows and floods originate both on the slopes of active volcanoes in the beds of “dry rivers,” and beyond the area of recent volcanism. The solid component of debris flows includes volcanogenic deposits, moraine, colluvial, and deluvial material. Traces of rain debris flows were observed in the catchments of channel and slope types. In the spring and at the beginning of summer, debris flows could be formed by a combination of rain and snowmelt. According to dendrochronological data for the Avacha Volcano area, the frequency of rain debris flows averages 11 years for large events and 3–4 years for small ones. The debris flow period lasts from June to October, and the period of the highest debris flow hazard is July–August.

In the Sredinny Range to the north of 58°N, slush flows prevail (Budarina and Perov 1984).

In 2007, an extraordinary event occurred in the Geyser Valley. A large landslide was formed, which blocked the valley of the Geyzernaya River, transformed to a debris flow and destroyed a number of geysers. No casualties were reported (Leonov 2007; Dvigalo and Melekestsev 2009).

Small debris flow catchments are typical for the Kuril Islands. For example, on the Kunashir Island, the debris flows originate on the 80–100 m high cliff and their channels are 0.4–1.0 km long (Korotkiy and Makarova 2006). According to reports, debris flows caused damage to motor roads in the north of the Paramushir Island and on the eastern coast of the Iturup Island (Fleishman and Perov 1976). In 2009, the Sarychev Peak volcano eruption on the Matua Island triggered a series of large lahars (Grishin 2011).

The damage from debris flows in the Kamchatka and Kuril debris flow province is insignificant because its territory is just slightly developed. The Avacha Volcano is a source of debris flow hazard for the town of Petropavlovsk-Kamchatsky and the Ebeko Volcano for the settlement of Severo-Kurilsk (Laverov et al. 2005). Debris flows from the Koryak Volcano disturb the agricultural lands near the town of Yelizovo, and those from the Shiveluch Volcano affect the transportation along the Klyuchi-Ust-Kamchatsk motorway.

5.2 Cold zone

D. **West region** includes Kola and Polar Urals debris flow provinces.

9. **Kola debris flow province** (the Murmansk Region) includes small mountain massifs of intrusive rocks in the western part of Kola peninsula. They can be divided into two groups: (a) Khibiny and Lovozero Tundras, higher and deeply dissected; (b) Chuna and Monche Tundras, Volchiy Tundras, Salnye Tundras, and the Chiltald massif. Average absolute elevations of the massifs are 800–1000 m; relative altitudes are 500–700 m. The dominating landscapes are mountain taiga and mountain tundra. Specific features of debris flow processes are described below with the reference to the Khibiny Mountains, the best studied and the most active in terms of debris flows (Perov 1966; Boyarskiy et al. 1979; Bozhinskiy and Myagkov 2001; Chernouss et al. 1998).

Slush flows and rain-induced debris flows are formed in the Khibiny Mountains; the dominating type is snow debris flows (the slush flow subtype). The zone of origination lies in the mountain-tundra belt; the accumulation zone is within the mountain taiga. The period of slush flows is May–June; average frequency is once every 10 years. The recorded events fall within the period from April 28 till June 10 (Zyuzin 2006). The mass slush flows were recorded in May, 1977 and 1987. In 1977, debris flows covered distances from 1.7 to 3.5 km; the volume of transported material was 40×10^3–50×10^3 m^3. The slush flow deposits were 3–7 m thick; they were composed of firn snow with debris (accounting for about 5% of the total volume).

Rain-induced debris flows are formed in the small slope catchments. They were recorded, for example, in the summer of 1960 in the catchment of the Kunyok River. During the spring snowmelt with contribution of rain, mountain mud floods could occur in river beds.

10. **Polar Urals debris flow province** covers the northern part of the Ural Mountains—the Polar and Subpolar Urals. It includes parts of the Arkhangelsk and Tyumen regions and the Komi Republic. Absolute elevations average 900–1100 m, relative altitudes are 600–800 m. Mountains are built of metamorphic, effusive, intrusive rocks and belong to the zone of continuous permafrost. The mountain-tundra and glacial-nival landscapes are

predominant. The recent glaciation is presented by 143 glaciers with a total area of 28.7 km^2 located at 400–1300 m above sea level. The Alpine-type relief and glacial deposits in the upper courses of valleys come from the glaciation.

The main genetic type is slush flows. These are widespread within the axial (snowy) zone of the Urals. The period of activity is May–June. Slush flows were recorded in June, 1958, 1965, in May, 1973, and in June, 1975. Their formation is conditioned by a rise of air temperature (by 7°–10°) within 2–3 days (Khodakov and Ilyina 1989).

The volume of transported debris material is usually 10×10^3–30×10^3 m^3, the maxima being 50×10^3–100×10^3 m^3. The largest volume of slush flow deposits recorded in 1973 in the catchment of the Bolshoy Poypudyna River amounted to 500×10^3 m^3 (Poznanin 1975). This is the maximum value for snow type debris flows in Russia. The frequency of slush flows in the Polar Urals is once every 7–10 years.

The mountain mud floods are less often formed as compared with slush flows. Two such floods were recorded in the Subpolar Urals in the upper courses of the Naroda River (Kemmerikh 1961, 1964). The first was formed on May, 1954, after a snow dam outburst; it covered the distance of more than 10 km and demolished the bridge. The second arose on July 16, 1959, after a heavy rain (60 mm of precipitation within 6 h). The water level rose by 1.5 m; after the water decline there was a layer of unsorted rock debris on the flood plain surface.

E. **East region** includes Putorana, Verkhoyansk and Kolyma-Chukchi debris flow provinces.

11. **Putorana debris flow province** occupies the Putorana Plateau. This massif is built of basaltic rocks. It is highly lifted and deeply dissected northwest part of the Central Siberian Plateau. The prevailing absolute elevations of flat tops are 800–1000 m, the depth of dissection is from 400 to 700 m.

The debris flow phenomena are rather poorly studied. The first data about the debris flow events are presented in Komlev (1957). Perov (1981) revealed a wide occurrence of debris flows, domination of slush flows and their frequency.

The debris flow phenomena are widespread within the whole plateau. High degree of hazard is characteristic of the northwest part of the plateau, while low degree is mainly typical for the southeast part. Debris flows are of snow and rain genesis with predominance of snow-melting triggered debris flows (slush flows). The volume of material transported by 14 recorded slush flows was 10×10^3 m^3 for 7 events, 10×10^3–3.6×10^3 m^3 for 6 events and up to 120×10^3 m^3 for one event. The frequency is 4–5 years. The debris flows are formed during the spring snowmelt, in May–June; the time interval for recorded events is between May 28 and on June 21. Along with the slush flows the mountain mud floods are formed during the same period. They originate owing to the outbreak of dams formed by slush flow deposits which are carried by the tributaries to the channel of the main river.

Slush flows of the Putorana Plateau are mainly formed in small valleys about 3 km^2 in area. The forward front of flows is about 4–7 m high, increasing up to 10–15 m within channel necks and turns. Slush flow deposits are up to 0.5 m thick debris layers, with tree fragments. The maximum size of transported boulders is 0.5–2.0 m.

Rain-induced debris flows occur in July–August. They belong to two groups—small slope and valley (channel). The debris flows in the zone of economic development could cause damage: for example, on June 11, 1990, a slush flow on the Aiken River destroyed a drilling rig. Several protective constructions (dams) are in operation.

12. **Verkhoyansk debris flow province** includes the Verkhoyansk Mountains and, further to the southeast, the Suntar-Khayata and Sette-Daban ridges, and the Chersky

Highland. It is located within the Republic of Sakha (Yakutia), the Magadan Region and the Khabarovsk Territory. Average absolute elevations of the mountains are 900–2600 m, and relative altitudes are from 400 to 900 m. Mountains are mainly built of poorly metamorphosed sandy-argillaceous rocks with effusive and intrusive rocks. Mountain-tundra and glacial-nival landscapes are predominant; the permafrost is continuous; there are recent glaciers in the highest ridges with higher precipitation, and vast ice fields are developed at their foothills (the Suntar-Khayata and the Ulakhan-Chistay ridges).

Ananyev (1967) recorded the evidence of debris flows in the upper courses of the Kolyma River, in the Annachag Ridge. Snow, rain and occasional seismically induced debris flows are characteristic of the province. Slush flows occur practically everywhere, mainly in the middle mountains. They are formed within small watersheds of temporary or permanent watercourses, in the source areas of main rivers and their tributaries. Average parameters of slush flow catchments in the Magadan Region are as follows: the area is 3.5 km^2, the length of watercourse is 3.2 km, the channel slope is 0.129.

The slush flows are formed in May–June owing to the sharp rise in air temperature during the snowmelt. On June 4 and 20, 1980, the slush flows were recorded in the Del-Urekchen Mountains; in June, 1977, they occurred on the Magadan-Yakutsk motorway (Nefedov and Kuznetsov 1983). In June, 1980 slush flows went down in the upper courses of the Seymchan River and in May, 1981, in the Tuonnakh massif. According to the results of the dendrochronological analysis, the average frequency of debris flows is one event per 5 years.

Rain-induced debris flows are widespread in high and middle mountains with the Alpine-type relief. They are triggered by heavy rains in July–August, in certain areas—with contribution of melt water from glaciers and ice fields. On July 23, 1964, a rain debris flow was observed in the catchment of the Sobopol River, in the north of the Verkhoyansk Mountains (Bashlavin 1968). The floodplain and banks were eroded by the flow and new channels were formed. Numerous rain debris flows occurred in July–August in the upper courses of the Adycha and Agayakan rivers, near the Ust-Nera settlement in 1958, 1959, 1961, and 1962 (Fleishman and Perov 1976). The water level of the rivers rose by 2–5 m, the volume of transported debris masses was from 5–10 to 40–50 thousand m^3. The catchments of the upper and middle courses of the Okhota, Kukhtuy, Ulbeya and Inya rivers are the areas of the active manifestation of rain-induced debris flows (Vinogradov 1980). The mountain mud floods are characteristic of the small valley debris flow catchments of middle mountains (the Chersky Highland). The volume of transported debris material is rather small, so the fans are poorly developed and debris flow levees are replaced by flat strips of accumulation along the channel. The small slope debris flows caused by heavy or steady rains are widespread.

Formation of seismogenic debris flows is possible within the province which is confirmed by the events on May 18, 1971, near the Ust-Nera settlement, in the catchment of the Artyk River in the Chersky Highland (Belyi et al. 1971). The grade 9 earthquake caused the failure of partially thawed soil masses on the slopes; debris avalanches transformed into a debris flow in the main valley of the Kobdi stream.

The degree of debris flow hazard is average and high within the deeply dissected Alpine-type ridges and massifs, and low and average in the other areas.

13. **Kolyma-Chukchi debris flow province** is located within the Magadan Region, the Kamchatka Territory and the Chukotka Autonomous Area. It includes medium-height and low mountains on the right bank of the Kolyma River and the Chukotka Peninsula and the Koryak Mountains. Absolute elevations of the mountains are 500–1800 m, relative

altitudes are 300–800 m. Sandy-argillaceous sedimentary rocks, granites and volcanogenic rocks compose the mountains. The mountain-tundra landscapes dominate.

Debris flows of rain and snow-melting genesis are formed in the Kolyma-Chukchi province; the latter are predominant. Snow debris flows (slush flows) are formed in May–June; their frequency and parameters are close to those of slush flows in the neighboring Verkhoyansk province. On June 5, 1991, a slush flow on the Kekurna River near the Pevek settlement took the lives of eight people and destroyed temporary constructions (Mochalov and Gorin 1992). It originated because of the sharp increase of air temperature during June 1–5 which led to the intensive snowmelt and failure of the oversaturated snow layer 3–4 m thick. Such flows are formed in the catchments not exceeding 20–25 km^2.

Rain-induced debris flows occur at the beginning and in the middle of summer. Between June 20 and 25, 1977 and 1978 rain debris flows were recorded in the Omsukchansky Ridge in the west of the province (Nefedov 1982). Both snow melting and rain participated in their formation. On July 23, 1977, rain debris flows went down in the Koryak Mountains in the east of the province (Kuznetsov and Bulatov 1980). The flows were formed as a result of steady rains. According to dendrochronological data, the frequency is once every 6–8 years. Debris flows originate in small valleys or on slopes.

The degree of debris flow hazard is low and average within the province.

F. **Arctic region** consists of Taymyr and Polar Insular debris flow provinces.

14. **Taymyr debris flow province** is located in the Krasnoyarsk Territory. Debris flow processes occur in the highest eastern part of the Byrranga Mountains with recent glaciation. Average absolute elevations of the mountains are 700 m, and the depth of dissection is 300 m. Mountains are mainly built of metamorphic and crystalline rocks. Mountain-tundra and glacial-nival landscapes are predominant.

Slush flows and mountain mud floods are formed within the Taimyr province. The first are formed on the surface of glaciers owing to the failure of oversaturated snow layer, the second—in narrow valleys of the periglacial zone owing to the outbreaks of the snow-field

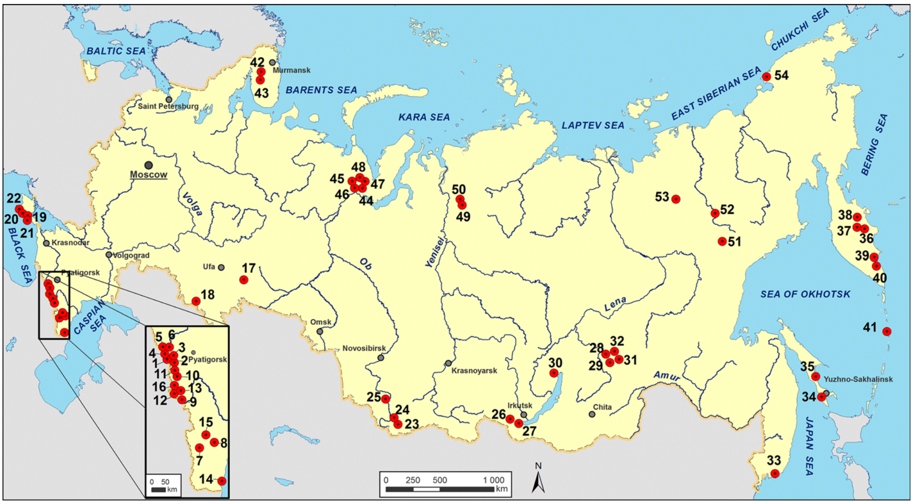

Fig. 7 Sites of debris flow events in Russia. Names of valleys and detailed information included to Table 2. Numbers of sites correspond to numbers in Table 3

dams. A slush flow was recorded in July, 1967, on the glacier surface; it was caused by intensive snow melting as a result of sharp warming (Fleishman and Perov 1976).

15. **Polar Insular debris flow province** covers the archipelagoes of Franz Joseph Land, Novaya Zemlya, Severnaya Zemlya, and the Wrangell Island. Administratively, they belong to the Arkhangelsk Region, the Krasnoyarsk Territory and the Chukotka Autonomous Area. About 30% of the islands is under contemporary glaciation in the form of ice sheets and domes. Ice and rocky surfaces are located 200–700 m above the coastal plain or the sea level; thus the glacial-nival landscapes dominate.

In general, the debris flow process is poorly developed. During the periods of intensive melting on the outskirts of ice sheets and domes and in the periglacial zone slush flows, mud flows are sometimes formed. Their origination is promoted, in particular, by the outbursts of temporary supraglacial lakes, and breaks of snow avalanche dams in the narrow periglacial valleys. In 1956, a slush flow was recorded on the Bryce Lake, the Franz Joseph Land. On July 29, 1958, a debris micro-flow was observed on the moraine ridge slope of the Shokalsky Glacier, the Severny Island of Novaya Zemlya (Svatkov 1963).

5.3 Location of sites with debris flows

Places of remarkable debris flows mapped on Fig. 7.

Brief description of the debris flow provinces is given below. The list of important events included to Table 3.

6 Conclusions

The total area of debris flow territories of the Russian Federation accounts for about 10% of the area of the country. The highest debris flow activity located in Kamchatka-Kuril, North Caucasus, and Baikal debris flow provinces. The largest debris flow events connected with volcano eruptions. Maximum volume of debris flow deposits per one event reached 500×10^6 m^3 (Kamchatka Peninsula). In the mountains of the Greater Caucasus, it is due to the great absolute and relative elevations and the vast glaciation which is at the degradation stage. The maximum volume of transported debris material in the Caucasus amounts to 3×10^6 m^3, the density of debris flow courses is high. In the Baikal debris flow province high debris flow activity is characteristic of the ridges lying in the axial part of the Baikal rift zone (the East Sayan Mountains, the Khamar-Daban Ridge and the ridges of the Stanovoye Highland). The "live" tectonics, contrasting relief and the high seismic activity are typical for this province.

The largest areas of potential debris flow hazard are within the Altai and Amur debris flow provinces where mountain taiga landscapes dominate. The negative role of economic activities in the activation of the debris flow processes is the most pronounced in the South Urals and Sakhalin debris flow provinces—the areas of industrial, agricultural, and silvicultural development.

The duration of the debris flow period decreases from the southern debris flow provinces to the northern ones (from 12 to 3 months). The debris flow period is 4–6 months long within the warm zone, and 3–4 months long within the cold zone. Volcano-induced debris flows (lahars) in the Kamchatka-Kuril debris flow province can occur during all periods of the year. The debris flows could form all the year round in the Caucasus and in Crimea as well. The period of the highest debris flow activity (accounting for more than

Table 3 Examples of debris flow events in Russia: location, dates, types and consequences

Region–province	Site no.	Place name	Type/trigger	Date	Volume, $\times 10^6$ m^3	Impacts, damages, and causalities
I-A-1 Northern Caucasus	1	Dzhalovchat (tributary of Adyr-Su River)	Glacial/rainfall	1–3.08.1940	3	2 Montaneering camps destroyed
	2	Kullumkol-Su (tributary of Adyr-Su River)	Glacial/rainfall	19.07.1983	0.33	1 Mountaineering camp destroyed
				3.08.2011	0.3	
	3	Gerkhozhan-Su (tributary of Baksan River)	Glacial/rainfall	1934		
				1937		
				1960		
				1961		
				1962		
				1977		
				1983		
				1999		
				18–25.07.2000	3	Destroyed check dam, the bridge, the channel for the passage of debris flows, buildings. Baksan River was dammed, Tyrnyauz city was partly flooded. 8 victims. Significant damage was caused to economy and industrial factories
	4	Bashkara Lake (Baksan River basin)	GLOF	1958		
				1959		
	5	Azau Lake (Baksan River basin)	GLOF	1978		
				2011		

Table 3 continued

Region–province	Site no.	Place name	Type/trigger	Date	Volume, $\times 10^6$ m^3	Impacts, damages, and causalities
	6	Birdzhalychiran Lake (Malka River basin)	GLOF	2.08.1909	0.425	Debris flow are destroyed the baths of thermal water sources, 1 house, huts and tents, ruined trails
				11.08.2006	0.55	Debris flow are destroyed the baths of thermal water sources, ruined roads and bridge
	7	Kakhab-Rosona Lake (Temir River basin)	GLOF	28–29.08.1969	1	
				07.1971		
				24–25.08.1972		
				2–3.08.1974		
				6.08.1974		
				14.07.1975		
				24.07.1975		
	8	Intitlyar River (tributary of Avarian Koysu)		28–29.08.1969	0.8	Destroyed roads, 2 bridges, power lines
				24–25.08.1972		
				3, 6.06.1974		
	9	Genaldon River (tributary of Gizeldon River)	Ice-rock avalanche/ debris flow	3.07.1902		32 Victims, destroyed 17 mills, destroyed buildings near thermal springs, 1730 cattle died
				20.09.2002	115	125 Victims, destroyed buildings near thermal springs
	10	Gyulchi-Su (tributary of Cherek Balkarskiy)	Rainfall	16.07.2011	0.2	
	11	Multiple debris flows	Rainfall	1953		Multiple damages
				1963		

Table 3 continued

Region–province	Site no.	Place name	Type/trigger	Date	Volume, $\times 10^6$ m^3	Impacts, damages, and causalities
				1967		
				1983		
				2002		
				2011		
				2014		
	12	Kasaykomdon (tributary of Ardon River)	Rainfall	12–15.07.1938	0.12	Destroyed road
				16.08.1953		
				06.08.1967		
				23.07.1975		
				1983		
				1986		
				1987		
				1990		
	13	Sadon (tributary of Ardon River)	Rainfall	23.06.1914	0.1	Destroyed village Sadon blurred road and destroyed 3 bridges
				12–13.07.1958		Destroyed 50 houses in the villages of Upper and Lower Sadon, bridges, dam, power station, diversion canal, the road
				09.08.1937		
				17.08.1953		
				10.07.88		
				21.06.2002		
				03.2004		
				23.07.2014		

Table 3 continued

Region–province	Site no.	Place name	Type/trigger	Date	Volume, $\times 10^6$ m^3	Impacts, damages, and causalities
	14	Derbent City	Rainfall	10.10.2012		6 Victims
	15	Muni village (Andiyskoe Koysu basin)	Rainfall	21.04.2014		Debris flow was wash away 4 cars
	16	Tseyadon (tributary of Ardon River)		23.07.1975	0.3	
I-A-2 South Urals	17	Aj River in Zlatoust city	Antropogenic/ rainfall	17.07.1966	0.01	Destroyed bridges, flooded with mud factory
	18	Tuzlukkol	Antropogenic/ rainfall	24.06.1979		Destroyed bridge, eroded soils, inundated crops on an area of 1300 hectares, loss of cattle
I-A-3 Crimea	19	Alushta City		1899		
	20	Ay-Serez	Rainfall	18.07.1911	0.1	6 Victims, destroyed 10 houses, 30 barns, 30 houses severely damaged, blown 1000 cartloads of timber. Destroyed orchards and vineyards in the valley Voron.
				09.06.1998		1 Victims, destroyed footbridges, retaining walls, water pipes and irrigation network, blurry road, entered the vineyards.
	21	Kutlak River	Rainfall	07.1967		20 Victims, including 15 children
	22	Demerdzhi	Rainfall	12.08.1997	0.03	
I-B-4 Altai	23	Aktru River	Rainfall	24.06.1984		
	24	Maashey Lake (Aktru River basin)	Rainfall and GLOF	14–16.07.2012		
	25	Sarasa village (Sarasa River)	Rainfall	7.06.2016		Damage 12 houses, blurred roads

Table 3 continued

Region–province	Site no.	Place name	Type/trigger	Date	Volume, $\times 10^6$ m^3	Impacts, damages, and causalities
I-B-5 Baikal	26	Arshan village (Kyngarga River basin)	Rainfall	25–27.06.1912	1.5	Multiple debris flows. 1 victim, 9 houses destroyed, 52 green buildings, bridges destroyed, 119 children evacuated, 212 people resettled.
				17–18.07.1962		
				26.07.1971		
				28.06.2014		
	27	Sludyanka River (Hamar-Daban Range)	Rainfall	1915	0.27	15 Houses destroyed, 50 houses damaged.
				20.06.1960		8 Houses destroyed, blurred and flooded railways
				28–29.06.1934		
	28	Leprindo Lake, Kodar Range	Rainfall	28.07.2002		Multiple debris flows. Blurred and flooded railways
	29	Sredniy Sakukan (Kodar Range)	Snowmelt and snow avalanche dam outburst	13.07.1976	0.02	
	30	Kunerma River (Baikalskiy Range)	Snowmelt and rainfall	21.05.1982		
	31	Chara River, Udokan Range	Rainfall	10.08.1983		Multiple debris flows. Debris flows destroyed are 7 bridges, few kilometers of the road, in the Naminga village destroyed houses and household buildings
	32	Byjiki River (Kodar Range)	Rainfall	21.07.2012	0.15	Multiple debris flows
I-C-6 Amur	33	Partizansk	Rainfall and antropogenic	22.05.2004	0.2	Clarifier outburst, damage railway and 14 railcars

Table 3 continued

Region–province	Site no.	Place name	Type/trigger	Date	Volume, $\times 10^6$ m^3	Impacts, damages, and causalities
I-C-7 Sakhalin	34	South Sakhalin	Rainfall	5–7.08.1981		282 Debris flows. Destroyed roads and railways, power line. Damage houses in cities of Nevelsk, Kholmsk, Uglegorsk
	35	South Sakhalin	Rainfall	12–14.08.1993		70 Debris flows. Destroyed roads and railways between the village Vostochnyj and Makarov City
I-C-Kamchtka-Kuril	36	Sukhaya Khapitsa River, Golubelnaya River, Chernova River, Bezymyannyj volcano	Eruption and snowmelt	30.03.1956	500	The largest debris flow in Russia. No destroyed buildings, no victims
	37	Krutenkaya River, Kirgurich River and other river, Klyuchevskoy volcano	Volcano sector collapse, eruption, and snowmelt	25.01–25.05.1932		
				01.01.1945		
				30–31.07.1993		
				01.10.1994		
				22–24.04.2007		
				8–9.12.2008		
	38	Baydarnaya, Kabeku, Bekesh, Kamenskaya, Sukhoy Ilchinets rivers, Shiveluch Volcano	Eruption, snowmelt, and rainfall	1–2.03.1854		Blockage of road Klyuchi–Ust-Kamchatsk
				12.11.1964		
				22.04.1993		
				19–20.05.2001		
				01.2002		
				9.05.2004		
				27.05.2005		

Table 3 continued

Region–province	Site no.	Place name	Type/trigger	Date	Volume, $\times10^6$ m^3	Impacts, damages, and causalities
				22.09.2005		
				29.03.2007		
				06.05.2007		
				27.04.2009		
				17.11.2010		
				21.08.2011		
				26.04.2012		
	39	Koryakskiy Volcano		2009		
	40	Avacha Volcano		1938		
	41	Sarychev volcano, Matua Island	Eruption and snowmelt	12–16.06.2009	0.3–0.4	
II-D-9 Kola	42	Khibiny	Snowmelt and rainfall	14.05.1977	Average 0.04–0.05	40 Slush flows
	43	Gakman River, Hibiny	Snowmelt and rainfall	19.05.1988	0.04	Destroyed drainage dam and damage industrial facility
II-D-10 Polar Urals	44	Shchuchia River	Snowmelt and rainfall	14.06.1958		
	45	Gena-Khadata River	Snowmelt and rainfall	14.06.1959		
	46	Khadata River	Snowmelt and rainfall	21.06.1965		
	47	Bolshaya Khadata River	Snowmelt and rainfall	06.1975	Max: 0.12	
				07.1976		
	48	Bolshaya Paypudyna River, Bolshaya Usa River	Snowmelt and rainfall	05.1973	Max: 0.5	

Table 3 continued

Region–province	Site no.	Place name	Type/trigger	Date	Volume, $\times 10^6$ m^3	Impacts, damages, and causalities
II-E-11 Putorana	49	Norilsk City	Snowmelt and rainfall	29.05.1955		
	50	Talnakh River	Snowmelt and snow avalanche dam outburst	06.06.1981	0.33	
				10.06.1981		
II-E-13 Kolyma-Chukchi	51	Agayakyan River	Snowmelt and rainfall	23.07.1958	0.015	
	52	Inyali River, Olchana River, Indigirka River	Snowmelt and rainfall	07.1959	0.005–0.04	
				08.1961		
	53	Adychi River	Rainfall	18.07.1962	0.04	
	54	Kekurnaya River	Snowmelt	5.06.1991		8 Victims, temporary buildings destroyed

50% of debris flow events) is about 2 months in all provinces. The period of the highest debris flow hazard is July–August in the European and Southern Siberian regions and August–September in the Pacific region. This is because the continental climate gives place to monsoonal climate in the south of the Far East (the typhoons causing debris flows are characteristic of the late summer and early autumn). In the east region of the cold zone, slush flows occur with double frequency compared to the western region (every 5 and 10 years, respectively). One of the main reasons is the intensive snowmelt under the sharply continental climatic conditions of the east region.

The unique debris flow hazard in the Kamchatka and Kuril province are volcanic debris flows (lahars), among which the extra-large flows were recorded (for example, the event at the Bezymyanny volcano on March 30, 1956, the largest in Russia).

The intensification of debris flow processes by economic activities is the most pronounced in the South Urals, Sakhalin, Crimea, and the Caucasus.

The debris flow parameters have been irregularly studied in different regions of Russia. In the future, it would be useful to make a map revision, because the climate change has led to a change in debris flow activity. In particular, in the polar and high-mountain regions, the glacier retreat led to the appearance of debris flow activity in the territories formerly occupied by glaciers. In other places, the disappearance of the ice has led to a desertification and to a change in the debris flow frequency. Digital elevation models can be used for automatic interpretation of the conditions of the debris flow formation. Also, there are wide opportunities for using remote sensing methods to correct the debris flow maps and inventories.

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