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DEBRIS FLOW AND LANDSLIDE HAZARDS UNDER CERTAIN TYPES OF ATMOSPHERIC CIRCULATION

ABSTRACT. Conditions of formation and development of landslides and debris flows in the Black Sea coast of the Caucasus and on Sakhalin Island were considered. They are formed under the influence of heavy rainfall under the influence of the Mediterranean cyclones outlet in the Black Sea coast of the Caucasus and of the Pacific cyclones outlet on Sakhalin Island in the same macro-circulation processes. Activity of landslides and debris flows in these regions has been shown to be connected with certain types of atmospheric circulation during the XX – the beginning of the XXI century. Based on these results, possible increase in the activity of landslides and debris flows, in the Black Sea coast of the Caucasus and Sakhalin Island, is suggested.

KEY WORDS: debris flow, landslide, atmospheric circulation, Black Sea coast of the Caucasus, Sakhalin Island

INTRODUCTION

Assessment of a debris flow and landslide hazard in the current period of unstable climate and possible extreme situations is very important. It is especially important for the Caucasian Black Sea coast. These processes, which constantly threaten tourism and the economy there, result from mass construction projects such as those expected in preparation for the XXII Olympic Winter Games of 2014 in Sochi. Assessment of a debris flow and landslide hazard on

Sakhalin Island is also very important in connection with the increase of the natural extremes frequency. More than 100 towns and villages are subjected to the influence of these processes. Annually, landslides remove from the use dozens kilometers of railways and highways and complicate the construction of many objects. Direct damage to roads and highways alone is estimated to be hundred thousands of rubles annually; the indirect damage associated with lost economic benefits from prolonged interrupted road network conductivity and construction is also high, but it is difficult to estimate it exactly. This paper presents the assessment of a hazard of debris flow and landslide made through analysis of their activity and the degree to which they affect the territory. Data on the debris flow and landslide activity in the past and present were analyzed using data on basic variable factors of their formation – meteorological and anthropogenic, in their interaction with geomorphological conditions.

METHODS AND DATA

Initial data in the assessment of a mudflow hazard included information on previous debris flows in the region under study, the data of the Sakhalin hydro-geological expedition and other organizations as well as meteorological data: air temperature and precipitation measurements from the nearest *hydrometeorological stations and the history of alternation of elementary circulation mechanisms*

((abbreviated to ECM) *in the atmosphere of the Northern Hemisphere according to the classification system by B.L. Dzerdzevskii [Dzerdzevskii, 1962; Kononova, 2010, 2011].* For each case of mud flow and landslide occurrence, the circulation type and meteorological indicators were identified.

CONTENT OF INVESTIGATIONS

The basic characteristics that are used to assess the hazard of debris flows and landslides include intensity of these processes on a territory, sizes of simultaneously formed debris flow cones, discharges and velocities of debris flows, and activity of debris flows and landslides manifestations. Here, activity of a process may be defined as the frequency of natural hazards or duration of the period between them [Landslides and mudflows 1988; Natural hazards of Russia, 2002]. The area destruction by debris flow and landslide is a typical occurrence; their activity depends on meteorological factors, seismic factors and human activity [Sheko, Malneva, 2002].

Debris flow activity changes with time and is subject to cyclic variations of different duration, depending on the factors causing debris flow development. The debris flow and landslide hazards in a particular basin or a region depend on the overall activity, which directly depends on the weather extremes [Lin, Lee, 2008; Ma, Huang, Xie, Zhong, 2008; Kononova, Malneva, 2007].

At present, the Black Sea coast of the Caucasus is characterized by a low hazard of debris flows. Predominantly, the debris flows there have a capacity of 10,000 m³ or less and a low frequency (once per 15–30 years). In the highlands, the debris flow frequency is higher: once per 8–15 years. The generating sources of the most hazardous debris flows are located in the belts of high and medium-height mountains. The capacity of debris flows can change from a few tens and hundreds m³ to 100,000 m³ or more. Activity of debris flows is closely connected with the regime of precipitation.

GENERAL CHARACTERISTICS OF DEBRIS FLOW AREAS

Depending on the factors that cause formation of debris flows, the following debris flow-hazardous regions in the Black Sea coast of the Caucasus can be distinguished in the territory under investigation:

Debris-flows that are formed on small watercourses and ravines flowing directly into the Black Sea. Their activity is especially high in the area of Novorossiysk city where water-stony debris flows are formed predominantly due to intensive rainfalls and dumps from cement quarries. The slopes are composed of the Upper-Cretaceous flysch and loose sediments of 2–3 m and sometimes up to 10 m thick. Debris flows along these watercourses have often damaged railways (in 1946, 1950, 1953 and 1958, as well as in 2009 and 2010), causing interruptions in train traffic, sometimes for 10 days. In the area stretching from Tuapse to Adler, the debris flows are formed mainly in landslide-generating sites. The character of these debris flows is usually erosive due to washing-out of accumulated sediments in stream channels [Landslides and mudflows, 1988].

Debris flows in high and medium-height areas of the Main Caucasian Ridge, which form due to washing-out of loose fragmental rock material entering the channels of temporary and small water streams in the form of mud avalanches, slides, and debris. In the alpine zone, ancient moraines play a great role in the formation of hard material.

Until the 1950s, recoding of debris flow manifestations was not conducted in the above-mentioned regions, with the exception of the most hazardous territories, i.e. the cities of Novorossiysk and Tuapse. Presently, data on the number of previous debris flows are also insufficient. In the 1970s, scientists from VSEGINGEO carried out a geo-engineering study of the Black Sea coast and the adjacent mountainous territory. As a result of these investigations, a map was

compiled, identifying the watercourses in the areas of Novorossiysk and Tuapse and some watercourses in the highland zone of the Mzymta River Basin as debris flow-hazardous. The dense forests of the highland and medium-height areas and small-scaled investigations (1:200000) made it impossible to characterize the debris flow streams of this territory in more detail, but it was noted that no high intensity of debris flows was observed. According to the data obtained during investigations in recent years, 40 mudflow-hazardous streams were registered in the Krasnaya Polyana area, 37 of them located in the Mzymta River basin (mainly from the northern slope of Aibga Ridge) and 3 streams located in the basin of the Psou River (the southern slope of Aibga Ridge).

It is noted that the most hazardous debris flows are formed in high mountains and medium-height areas along watercourses that cut through cirque moraines or along channels filled with slide material in the zone of clayey shale and argillites (streamlet Galion – 2, Vodopadnaya, Tobias, Sulimovsky and others). Due to the steep slopes of channels, floods in small debris flow-hazardous basins are characterized by short lag times, sharp rises and falls of water levels, and high water discharges.

As follows from these studies, during recent years the debris flow hazard on the investigated territory has grown, mainly as a consequence of the increased intensity of anthropogenic impacts and, in particular, by deforestation and the related erosion on the slopes. Generally, such tendency was observed in the Caucasus during the past several decades.

An increase in the intensity and activity of the debris flow process is considerably connected with the geological conditions of a territory under investigation and is observed in areas composed by metamorphic, terrigenous and flysch rocks of different ages, especially of the Lower- and the Middle-Jurassic period. The strength of clayey and aspid slates, found in the upstream of Mzymta River, is

highly dependent on the wetting degree. Of attention is the slight ductility of argillites, clayey shale, and aleurolites to weathering processes, especially in the areas of tectonic crushing. In many cases rocks are soaked and swollen or become even fluent. On clayey shale, such a zone with highly soaking heavy loams with inclusion of rock debris can have a thickness of 1 to 5 m. Typical for such rocks is a decrease in resistance to shearing and development of a sliding process, including in sites of originating debris flows. Simultaneous with this is decreasing resistance to erosive wash-out. It is natural that in the zone of the Lower-Jurassic and the Eocene-Oligocene clayey rocks that are less resistant to denudation, and the loamy slope formations of different genesis, mud-stony streams varying in thickness and density develop.

Investigations of the conditions of forming debris flows on the Black Sea coast of Caucasus and in the adjacent mountainous areas have established that the basic factor influencing their activity is the degree and regime of territory wetting.

Analysis of all known cases of debris flow formation makes it possible to note that a close linkage exists between precipitation and debris flows in the region under investigation, especially in lowlands [Methods of permanent forecast of exogenic geological processes, 1984]. Thus, in the area of Tuapse and Novorossiysk, the daily precipitation amount during mudflows exceeds, as a rule, 100 mm. Sources of hard stony streams there are small-sized landslides, detrital cones of ravines, covers of alluvial sediments at slope foots, and sediments from the channels washed out by floor erosion. The high mudflow hazard of the Tuapse region is evidenced by the sad events that occurred in the beginning of August 1991, which struck the mountains and the coast in the area of Tuapse-Sochi and spread to the northern macro-slope up to Maikop City. During the night from July 31 to August 1, heavy rain fell in these areas. The rainfall caused a high water level in the rivers

Table 1. Daily precipitation sums in August 2002

Settlement	Date	Daily precipitation sums (mm).	Long-term period average monthly precipitation sums (mm)
Novorossiysk	5	69.0	45
	6	12.8	
	7	8.0	
	8	58.2	
Anapa	5	24.6	34
	6	62.4	
	7	61.9	
	8	55.5	

and activated mudflows. A similar tragedy occurred there in October 2010.

In the area of Novorossiysk, the catastrophic manifestation of mudflows in August 2002 was also caused by anomalous precipitation. The center of catastrophic events was in the area of Novorossiysk city. Heavy rains covered the entire Krasnodar Region and caused mud streams. The precipitation amounts for those days are presented in Table 1.

Thus, on some days (5 and 8 August, in Novorossiysk, and August, 6–8 in Anapa), daily precipitation sums exceeded the long-term monthly averages.

The above-indicated precipitation amounts are indeed high. However, in July in the same area, the rainfall was also heavy, Novorossiysk, 23 July – 42.4 mm, 24 July – 89.9 mm), yet here were no reports of floods or debris flows. The first significant manifestation of debris flows happened on 6 August and the next rains fell on the territory when it was already conditioned for the intensification of exogenic processes by the weather of the previous period, thereby causing mass debris flows and intensification of landslides in the surface sediments. This event is evidence that previously existing meteorological factors play a significant role in the exacerbation of the effect of short-term precipitation on debris flow generation.

It is known that in the northwestern part of the Black Sea coast, the most mudflow-hazardous in the sliding and erosive-sliding sites were the years with increased humidity – 1960, 1962, 1967, 1970, etc. In these years, the meteorological stations of Anapa and Novorossiysk recorded an increase of days with heavy rainfall. In the area of Tuapse and Novorossiysk, the daily precipitation amount exceeded 100 mm in all cases of debris flows. As we have established, in this part of Caucasus, the daily maximum precipitation is highest in those years when the monthly and annual precipitation amounts considerably exceed the long-term period average precipitation sums.

It should be noted that the multi-year course of the annual precipitation on the Black Sea coast and in the adjacent territory of the North Caucasus (Sochi, Krasnaya Polyana) varies little. The seasonal variation in precipitation is also similar among stations in this region.

In several years (1924, 1932, 1937, 1939, 1940, 1953, 1955, 1958, 1967, 1977, 1988 – 1989, 2002), annual precipitation far exceeded the norm. The territory under investigation is characterized by a high homogeneity of the multi-year precipitation regime, as confirmed by the high correlation coefficients between the series of annual precipitation at different meteorological points. These coefficients are

equal to: Achishkho – Krasnaya Polyana – 0.89; Achishkho – Goitkh – 0.76; Sochi – Krasnaya Polyana – 0.89. However, according to the values of heat and moisture provision, the regime of meteorological factors in the highlands and medium-height areas significantly differs from that of the coast and the piedmont areas by both the sum of precipitation and the years with precipitation extremes.

Debris flows on the Sakhalin Island. The geological structure of the Sakhalin Island is dominated by the loose types: argillite, clays, aleuolite. Argillites practically become soggy easily. The clays also become soggy easily and particularly quickly lose strength when the mode of moistening changes. The territory is dominated by the areas where temperature and moisture regimes fluctuations occur frequently during springtime, which cause loss of strength of soils and increase of their weight, promoting landslides.

The high activity of landslide and mud flow processes depends, first, on meteorological factors: atmospheric precipitation and air temperature. In the last years, the highest activity was in 2002; the territory was subjected to extreme fluctuations of moistening.

FEATURES OF ATMOSPHERIC CIRCULATION

Debris flow formation on the investigated territory depends not only on absolute values of air temperature and precipitation amounts, but also on the character of weather in general which can be quantitatively expressed by the number of days with various macro-circulation processes in the Northern Hemisphere [Dzerdzeevskii, 1962].

For analysis of circulation conditions it is reasonable to use the classification of elementary circulation mechanisms (ECMs) of the Northern Hemisphere, developed by B.L. Dzerdzeevskii jointly with his graduate students. The information on the classification can be found also in [Kononova,

2010] or on the website www.atmospheric-circulation.ru [Kononova, 2011]. The entire variety of circulation processes in the Northern Hemisphere is represented in this classification by 41 ECMs. For each ECM the dynamic schemes of cyclone movement and anticyclone position is given, allowing the modeling of the manifestation of each ECM in any region of the Northern Hemisphere.

The history of ECM variability is compiled from 1899 to the present, indicating the appropriate ECM for each day. By comparing the time of debris flow intensification with the calendar of ECM alternation, we established the specific ECMs at which debris flows have occurred. In the erosion sites, these are the ECMs that cause intensive destruction of rocks due to frequent changes of their wetting state into drying and freezing into thawing, as well as intensive run-off of weathering products and wash-out of channel sediments.

In the sliding sites for the formation of debris flows, of importance are precipitation amounts and regimes that cause decreased slope stability. Here, debris flows are correlated with those macro-circulation processes at which the probability of rainfalls is 60% or greater, or 10% or less, the latter most often characterized by heavy rains.

It was established that the most dangerous weather for sites of debris flow origination in the research areas on the Black Sea coast and in the adjacent territory of the North Caucasus is connected with those ECM patterns at which Mediterranean cyclones move over the Black Sea coast of the Caucasus. The unstable weather, brought by these ECMs, forms favorable conditions for alternate wetting-drying of easily breakable rocks in debris flow-generating sites and accumulation of loose detrital rock materials; intensive rainfalls cause run-off of crushed rock materials and formation of liquid debris flows. The same ECMs are dangerous for the watershed of the Mzymta River and the adjacent areas of the Krasnodar Region. Their dynamic schemes are shown in Figure 1. In

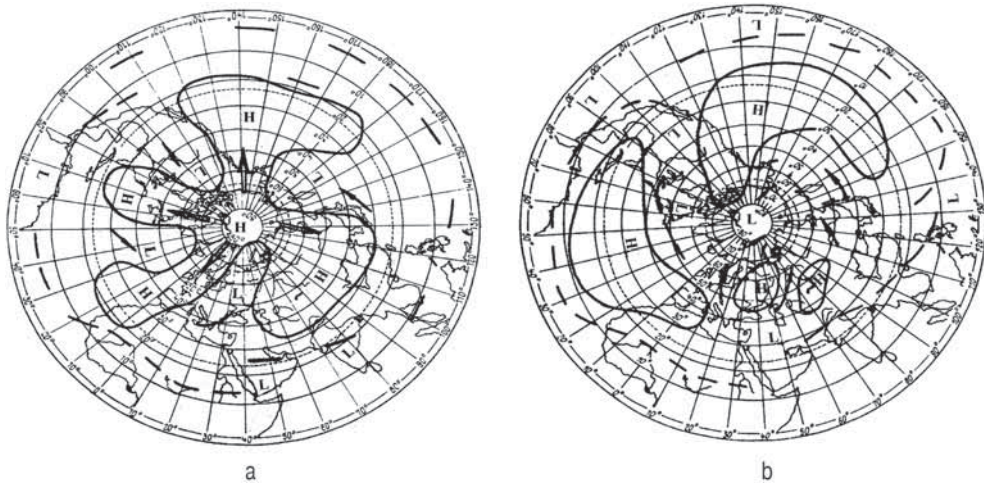


Fig. 1. Dynamic scheme of ECMs 12a (a) and 13s (b):

Letters 'H' and 'L' denote high atmosphere pressure (anticyclone) and low atmospheric pressure (cyclone), respectively

these schemes, it is clear that the southern cyclones enter the Black Sea coast of the Caucasus and Sakhalin.

On Sakhalin Island, in the same ECMs, the weather extremes are formed due to the Pacific southern cyclones outlet. The most significant precipitation on territory of Sakhalin and in the other parts of the Far East region are connected with ECM 13s (Viakhtu, 16.09.52 – 33.8 mm per day, Holmsk, 23.07.57 – 25.8 mm); ECM 9a, as well as ECM types 8 and 12. The frequency of these ECMs is increasing at present.

The typhoon output frequency on Sakhalin increases under ECM 13s. The calculations based on weather maps show that, in the last decennial events, frequency of typhoons near Sakhalin increased. The most powerful typhoons on Sakhalin for the last decennial events and types of atmospheric circulation, existed at this time, are presented in Table 2.

As defined earlier, very dangerous, for debris flow and landslide processes, is also weather under ECM 12a. Under this ECM, Sakhalin influenced by the area with considerable changes of weather that promoted mud

Table 2. The strongest typhoons in the Pacific and ECM in the period of its action over Sakhalin

Year	Date	Name of typhoon	ECM in the period of typhoons activity
1961	September 16–17		5d
1972	September 12–16	"Maria"	13s, 12a
1981	August 5–6	"Fillis"	13s
1992	August 14–17	"Robin"	13s
1996	September 23–26	"Violetta"	9b, 13s
2000	September 5–6	"Saomai"	13s
2002	July 11–15	"Chataan"	13s, 3
2002	September 2–3	"Rusa"	13s

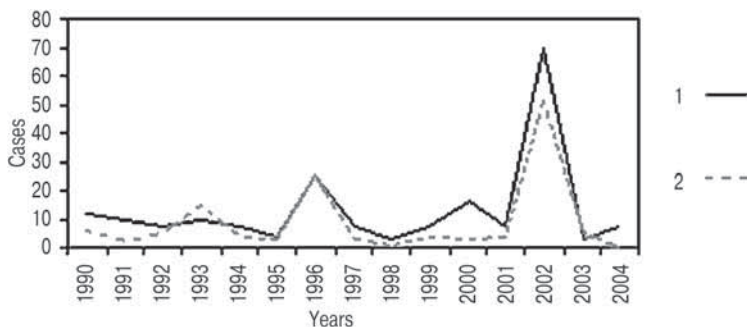


Fig. 2. Mud flow and landslide processes activity in the Makarov area during 1990–2004.

1 – landslide, 2 – mud flow

flows. In all cases, the activity of landslide and mud flow on Sakhalin was primarily associated with typhoons; weather patterns that existed for the entire period prior to the occurrence of these hazards are of great importance. For the center of Sakhalin, mud flows on clay types were associated with the most dangerous weather under ECM 13s, when intensive moistening promoted formation of debris flow. Changes of landslide and debris flow activities (per year) in 1990–2004 are shown at Figure 2.

In 2004–2008, the conditions were virtually completely stable in all areas of the observations, both on the western and eastern coast, which was due to the lack of humidity. [Gensiorovsky, Kazakov, 2009]; there was only a local increase in occurrences in Makarov in the spring of 2007, but this was

due to the intensive melting of snow (there were superficial landslides and mud flows within a very small area).

In 2009, on 22–24 June, there was a strong intensification of landslides and debris flow on Sakhalin Island [Gensiorovsky, Kazakov, 2009] at ECM 12bs (June 22) and ECM 12a (June 23–24). There were more than 50 cases of debris flow (mostly mud-stone and mud flow). Intense landslide activity was also recorded. These were mainly mud-streams – small- and medium-power landslides typical for this area.

In 2010 on Sakhalin, there were two periods of intensification on the western (Kholmsk and Nevelsk areas) and southern (Korsakov) coast. According to the information received from Yu.V. Gensiorovsky and N.A. Kazakov,

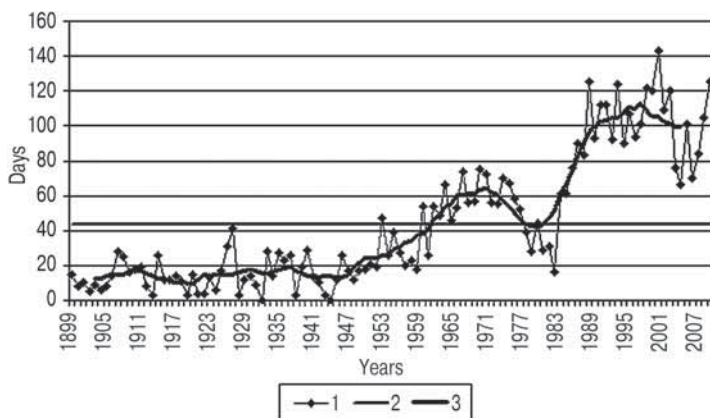


Fig. 3. Total annual duration of ECM 12a and 13s for 1899–2010:

1 – annual duration, 2 – average for 1899 – 2010, 3 – annual duration smoothed over 10 years

the massive intensification of events occurred in Nevelsk and Korsakov on 28–30 July (on 28 – ECM 8vs, on 29-30 – ECM 13s); on 10–12 August (ECM 9a), the massive intensification was recorded in the Kholmsk district [Musohranova, Gensiorovsky, Kazakov, 2010].

The total annual duration of these ECMs (Fig. 3) according to 2010 data significantly exceeds the average duration for 1899–2010. The recent tendency is depicted by curve 3 (10-year smoothing). As shown, the total annual duration of precipitation-forming ECMs, for the Black Sea coast and Sakhalin in the modern period, is the highest of all time since 1899. This suggests that, in the nearest 10–15 years, the risk of debris flows in these regions will remain high.

ANTHROPOGENIC INFLUENCE

The natural conditions of mudflow formation on the territory under study are significantly disturbed by anthropogenic activities, the intensity of which is presently increasing rapidly. All this considerably affects the geological environment. Land development causes flooding of the ground strata, rise of the groundwater level, soaking of the soil and a decline of its strength, which, in much of the region, is not high, as described above. When the natural and anthropogenic factors act jointly, the hazard of mud flows in rock complexes will be especially high.

Taking into account the construction of the Olympic buildings in Krasnaya Polyana, generation of stony components will considerably increase and, with anomalous wetting, can lead to formation of debris flows with a capacity of up to 200,000 m³ [Malneva et al, 2008].

The hazard of debris flow formation is explained by the fact that even small debris flows formed, for example, in water streams on the slope of the Aibga Ridge, can act jointly with the active landslides developed on the left- and right-hand shores of the Mzymta River. As a result, the Mzymta can be dammed by a catastrophic debris flow.

Therefore, special attention should be given to the assessment of the present-day activity of landslides of different genetic types and to their possible manifestations as sources of the hard component of debris flows.

Attention should be also paid to other areas with high landslide intensity in the Mzymta River basin, in particular, in the basin of the Medoveevka River, which can be associated with large-volume debris flows. Additionally, a very dangerous area is the basin of the Kepshi River, characterized by an extremely high risk of debris flows that are connected with landslide-originating sites. With the intensification of a landslide, the formation of a catastrophic debris flow of a capacity of up to 300,000 m³ is possible.

CONCLUSIONS

1. In the nearest years, one should expect an increased debris flow hazard on the Black Sea coast, in the adjacent mountainous areas and on Sakhalin due to the increasing intensity and activity of the debris flow formation process as a result of natural and anthropogenic factors.
2. With a considerable increase in debris flow hazard, debris flows in this region can form in locations with no previous debris flow activity. Due to the expected increasing technogenic load connected with the Olympic Games of 2014, the total impact of natural and anthropogenic factors can be especially high. Many economic objectives can be hindered by even small debris flows. Thus, for certain structures, including oil and gas pipelines and highways, even debris flows of low capacity will be dangerous. They can interrupt traffic for an extended period of time and cause significant material damage.
3. In connection with the current character of the atmosphere circulation and the high frequency of the south cyclone and the typhoon outlets in the years ahead, there exists a high danger of intensification of the landslides, debris flows and other disastrous natural processes on Sakhalin island. The

area of Makarov requires special attention; there, the landslides and debris flows are already intense and the intensification of these processes is possible in future years.

4. Although it is not possible to prevent catastrophic events, their negative consequences can be minimized through

systematic monitoring of hazardous exogenic processes.

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