OPEN ACCESS Freely available online

Journal of Geography & Natural Disasters

ISSN: 2167-0587

Research Article

Dangerous Slope Processes as a Result of Anthropogenic Impact: The Case Study on Sakhalin Island (Russia)

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ABSTRACT

Human activities produce snow avalanches, debris flows and landslides. In some cases, human actions can lead to previously non-existent avalanches, debris flows, and landslide complexes, thereby increasing the vulnerability of settlement areas to hazardous processes. Typically, anthropogenic slope processes are confined to mountainous regions and are associated with mineral extraction, road construction, building development, and the accumulation of material in floodplains and watercourses on mountain slopes featuring unstable layers. The authors propose classifying the anthropogenic genetic class of avalanches, debris flows, and landslides into three groups based on the extent of human influence on the development of these processes and their characteristics. This classification supports assessing and evaluating potential consequences of avalanches, debris flows, and landslides during the initial phases of economic activity planning.

Keywords: Dangerous slope process; Geologic hazard; Debris flow; Snow avalanche; Landslide; Sakhalin Island

INTRODUCTION

Debris flows, landslides, and avalanches are among the most common hazardous slope processes that cause significant damage to the population and economy of Sakhalin Island. One critical factor in their formation is anthropogenic activity, which leads to geosystem changes and the activation of dangerous geological processes. In some instances, newly created anthropogenic landscapes, including artificially formed relief features such as dumps, slopes of various barriers and excavations, and quarry berms, serve as sources for hazardous slope processes like mudflows, avalanches, and landslides. The development of these anthropogenic complexes expands the area affected by hazardous processes (*i.e.*, the ratio of the area occupied by mudflow, avalanche, and landslide complexes to the total area of the territory), complicating construction, mining, and farming while posing a threat to the local population [1].

Geological hazards in areas affected by human activity manifest locally within any region, often confined to constructing buildings and structures and laying roads. These hazards are primarily linked to excavation, storage of soil, the formation of road barriers, and the undercutting of slopes. However, they are most prevalent in mountainous regions, typically associated with mining, stockpiling, and rock-dumping from mine operations. In mountainous terrain, many of the dumps are situated in floodplains and along river and stream beds on weakly stable slopes, which can lead to the occurrence of multi-stage or cascading natural and artificial disasters: landslide → blockage of the riverbed or river valley → flooding → dam failure → catastrophic mudflow [2].

A typical example of hazardous exogenous geological processes in an anthropogenically modified area of Russia is the formation of a catastrophic landslide at the coal mine waste dump in the Zarechny open pit (Kemerovo region) on April 1, 2015. The landslide had a volume of 27 million m^3. It caused damage to power lines, blocked the Novokuznetsk - Bolshaya Talda public road, obstructed access to the Taldinskoye vocational school, and impeded a part of the Kyrgai River.

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Received: 31-Jan-2025, Manuscript No. JGND-25-36924; Editor assigned: 05-Feb-2025, PreQC No. JGND-25-36924 (PQ); Reviewed: 19-Feb-2025, QC No. JGND-25-36924; Revised: 16-Apr-2025, Manuscript No. JGND-25-36924 (R); Published: 23-Apr-2025, DOI: 10.35241/2167-0587.25.15.342

Citation: Bobrova DA, Kazakova EN, Rybalchenko SV, Kashdan AY (2025) Dangerous Slope Processes as a Result of Anthropogenic Impact: The Case Study on Sakhalin Island (Russia). J Geogr Nat Disasters. 15:342.

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The formation of avalanches, mudflows, and landslides in anthropogenic territories has been examined at various times by researchers from multiple Russian organizations, including the Research Laboratory of Avalanches and Mudflows at the Faculty of Geography, Lomonosov Moscow State University, the Avalanche Safety Center of Apatite, the Laboratory of Avalanche and Mudflow Processes at the Far East Branch of the Russian Academy of Sciences, the Research Center "Geodynamics" at Don State Technical University, and Kuban State University, among others. This issue is also pertinent in many populated mountain regions of Norway, the Indian Himalayas, China, Portugal, Belgium, New Zealand, Switzerland, and Canada, as well as France [3].

Although anthropogenic activity has long been regarded as one of the primary factors in the formation of mudflows, avalanches, and landslides, a comprehensive classification of human-related phenomena has yet to be fully developed. Furthermore, no measures are currently in place to plan anthropogenic activities considering the potential consequences of the emergence of hazardous slope processes.

Research into dangerous exogenous geological processes in anthropogenically altered areas is mainly descriptive and generally focuses on various geological phenomena. Varnes initially classified "rock, debris, and earth" within landslide-type classifications, which does not align with either the geological terminology for materials defined by origin or the geotechnical classifications based on mechanical properties. Additional principles have since been added to these classifications, particularly regarding the mechanisms of motion. Typically, changes in the parameters of specific snow avalanches, mudflows, or landslides due to anthropogenic influence are evaluated. These recent studies highlight the importance of human activities in shaping hazardous processes. However, they do not provide a comprehensive pattern illustrating how various anthropogenic interventions impact the natural environment, whether by enhancing or diminishing the activity of dangerous geological processes. At the same time, anthropogenic influences restrict our ability to predict hazardous events, necessitating their prior classification [4].

Some researchers propose distinguishing between different types of anthropogenic activity. However, the authors believe these classifications need to be refined, as they do not adequately reflect the diversity of various forms of economic activity. Hungr, Leroueil, and Picarelli classified only categories such as random anthropogenic fills, engineered anthropogenic fills, mine tailings, and sanitary waste.

Perov proposed a genetic classification of mudflow phenomena. In addition to the climatic and geological factors contributing to mudflow formation, the author identifies anthropogenic factors and categorizes mudflows related to economic activities into two types: Anthropogenic and natural-anthropogenic.

The division of the anthropogenic genetic class into types based on the degree of anthropogenic impact is quite logical. This approach enables us to view anthropogenic activities as a series of more specific types of activities and, accordingly, to assess the potential effects on the formation of hazardous slope processes depending on each particular kind of activity. The authors did not find classifications based on the proposed principle in existing publications. This work could be a starting point for further research and development in predicting dangerous slope processes, considering anthropogenic influence [5].

Therefore, the primary objective of this work is to characterize the various types of anthropogenic impacts on landslide, mudflow, and snow avalanche processes and evaluate changes in the descriptive characteristics of hazardous slope processes resulting from anthropogenic impacts on Sakhalin Island. This study does not consider changes in the conditions that lead to the formation of hazardous natural and natural-anthropogenic slope processes or alterations in their dynamic characteristics (such as flow velocity, initial consolidation pressure, friction parameters, mudflow or avalanche path, etc.).

MATERIALS AND METHODS

Field research utilizing archival data on landslide, mudflow, and snow avalanche disasters from 1912 to 2022, along with information about the peak activity period from 1872 to 2022, was conducted to examine the mechanisms and conditions that led to the formation of natural and natural-anthropogenic landslides, mudflows, and avalanches.

During this work, observations of the occurrence and development of debris flows and measurements of mudflow parameters were conducted. A set of engineering geological and meteorological data, along with the morphometric characteristics of mudflow basins, was processed. The authors examined recent publications on this issue produced by other researchers and conducted their own research [6].

The geological structure of landslides was determined using drilling and seismic survey materials from the landslide massifs. The environmental conditions triggering landslide, mudflow, and snow avalanche processes were established based on the analysis of observation data from hydrometeorological stations in Sakhalin Island.

Conditions for the formation of mudflows, landslides, and avalanche processes on Sakhalin Island. One of the regions with a high prevalence of dangerous exogenous geological processes is Sakhalin Island. Furthermore, this territory is undergoing active economic development, often increasing vulnerability to natural disasters. Sakhalin Island is situated in the Far East of Eurasia and bordered by the Sea of Okhotsk and Japan. The island stretches 948 km from north to south and has a width ranging from 26 to 160 km [7].

The territory of Sakhalin is characterized by low and medium-altitude mountains extending southward. The West Sakhalin Mountains dominate the western portion of Sakhalin Island, with the highest peak, Mount Vozvrashenie, reaching 1,325 meters. The East Sakhalin Mountains are located in the eastern region, with the highest point, Lopatin, at 1,609 meters. The Susunai and Tonino-Aniva Ranges can be found in the southern part of Sakhalin. The North Sakhalin Plain features highly dissected terrain and residual-denudation mountains ranging from 300 to 600 meters in elevation in the northern section of

Sakhalin. Sakhalin Oblast experiences a monsoonal climate marked by intense cyclonic activity, high precipitation, and frequent snowstorms.

The widespread occurrence of avalanches, mudflows, and landslides on Sakhalin results from a favourable combination of geomorphological and meteorological factors. High snow avalanche activity on Sakhalin stems from relatively high precipitation and an extended winter season. Permanent snow cover on Sakhalin is typically observed from October in the mountainous region of Middle Sakhalin and from late November in the coastal area of the southern part of the island. This snow cover reaches its maximum thickness during the second or third decade of March, attaining 250-400 cm in the mountains. It usually disappears in early to mid-May in the island's south and in late May in the north. The period of heightened avalanche activity, known as the avalanche cycle, varies from four months in the coastal region of South Sakhalin to eight months in the island's mountainous areas. Solid precipitation on Sakhalin averages 150-300 mm in the coasts and valleys, reaching 500-1200 mm in the mountains [8].

The avalanche complexes on the islands' territory can be categorized into mountainous, coastal, and plain areas. For instance, the average volume of a mountain avalanche ranges from 15,000 to 500,000 m^3, with a maximum exceeding 1 million m^3. Two snow avalanches of this size, measuring 1 million m^3 and 1.4 million m^3, descended on Chamginsky Pass (the mountains of Eastern Sakhalin) on January 3, 1991. Likewise, the avalanches in coastal complex terrain, found on the ledges of marine terraces and sheer cliffs, feature height variations of 5 to 200 m. The average volumes for these avalanches tend to be smaller, typically ranging from 1,000 to 100,000 m^3, with maximum volumes potentially reaching 30,000 m^3. In contrast, snow avalanches in valley complex relief are generated on the slopes of river terraces and ravines with height differences starting from 5 m, where the volumes can range from 50 to 500 m^3.

The high intensity of mudflow and landslide processes on Sakhalin results from several factors: Considerable depth of relief dissection (up to 1000 m); steep watershed slopes (35-50°); a significant amount of liquid precipitation, with average rainfall during the warm period (April-October) ranging from 300-400 mm in the North to 450-800 mm in the South; in the mountains, precipitation increases with elevation, reaching maximums of 1277 mm per cyclone, 230 mm daily, and more than 50 mm hourly; and the geological composition of the area, which includes weakly cemented siltstones, mudstones, and sandstones that are easily eroded and saturated, contributing clay fractions to the mudflow and forming a cohesive suspension, alongside intrusive solid, volcanogenic, and metamorphic rocks that provide the boulder component of the flows [9].

Both cohesive (mud and mudstone) and non-cohesive (suspended stream, slush flow) flows are formed on Sakhalin. The mechanism for the onset of debris flow includes debris slides (residual soil), rock compound slides (weak sedimentary rock), and clay flow slides (sensitive marine clay). The genesis of the water component comes from both rainfall and snowmelt.

The mudflow hazard period lasts from April to November. The average volume of mudflows in the Sakhalin region is generally insignificant, amounting to 500-1,000 m^3; however, the maximum volume can exceed 500,000 m^3, with the mudflow run-out distance reaching 16 km. Mudflows exceeding 100,000 m^3 occur once every 25 to 30 years, while those ranging from 50,000 to 100,000 m^3 happen once every 10 to 12 years. Slope mudflows (including mud and mudstone mudflows) of 100-500 m^3 (and occasionally up to 1,000 m^3) are actively formed on unmodified slopes and in erosion trenches with gradients greater than 25°. The mudflow run-out distance extends for tens of meters, the thickness of deposits varies from 0.5 to 4.0 m, and the density ranges between 1,800 and 2,000 kg/m^3.

The active formation of landslides features two peaks within the annual cycle: Late May to early June and August to October. The first peak occurs due to significant snowmelt, which quickly saturates soils with moisture and often leads to landslides. Rain during this period may trigger landslide activation. The second peak relates to heightened cyclonic activity, resulting in substantial liquid precipitation.

On Sakhalin Island, block landslides and debris slides occur in bedrock ranging from 8 to 10 m up to 200 m or more, with volumes exceeding 5.0 million m^3. Secondary block landslides and debris slides form on the bodies of ancient landslides, measuring between 5 and 10 m to over 50 m, with volumes surpassing 1.0 million m^3. Viscoplastic slumps develop in the overlying sediments, with volumes above 1.0 million m^3. Mudflows are most intensely formed in weakly lithified sandy-clay rocks, while debris slides occur in deluvial sediments. These modern landslides are generally small and low in power, developing in water-saturated slope sediments or on the bodies of ancient landslides.

Instances of mudflow, landslides, and avalanche formation on Sakhalin Island are noteworthy. A typical example of a hazardous slope process resulting from human activity was documented on July 20, 2009, by staff from the Sakhalin branch of the Far East Geological Institute of the Far East Branch of the Russian Academy of Sciences: A technogenic mudflow originated from a dump at the Listvenichny quarry, located on the slope of Mount Medika. The regular formation of small mudflows (ranging from 0.5 to 1,000 m^3) from this quarry dump is noted. However, in recent years, due to the intensive expansion of the quarry and an increase in the volume of waste rock set aside for storage, two instances of more extensive mudflow formation have been recorded: 10,000 m^3 and 15,000 m^3 in 2009 and 2013, respectively. The total volume of mudflow deposits in the valley of the unnamed creek is approximately 55,000 m^3. Debris flows have destroyed 3.5 hectares of forest in that area; this area is depicted in Figure 1. Over the past 20 years, more than 15 cases of anthropogenic mudflows have been observed on Sakhalin.

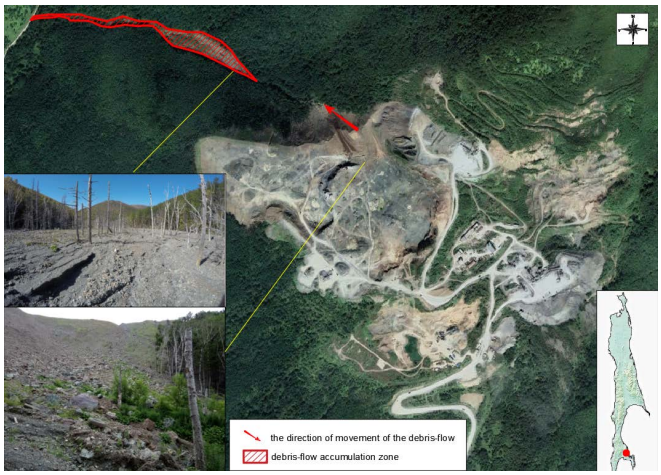


Figure 1: Rock dump in the upper part of the unnamed creek basin (slope of Medica, Susunai Range, Sakhalin Island) (left) and anthropogenic mudflow deposits in the valley of this creek (right).

Another example from Sakhalin involves a recent landslide formation due to waste dumps, specifically a flow slide with a volume exceeding 500,000 m^3. This occurred from the soils of the Lopatinsky-Vostochny overburden dump at the Gornozavodsk brown coal deposit in the village of Gornozavodsk, Nevelsk district (southwest coast of Sakhalin Island) on May 14, 2018. The event destroyed a private home and farm buildings, leading to the loss of ten cows. The landslide threatened to block the spawning river Lopatinka, which also serves as a source of domestic and drinking water for the village. In Gornozavodsk, over 4,000 residents faced the risk of environmental and humanitarian disasters; this area is depicted in Figure 2.

The soils were deposited on the valley floor and in the stream bed, leading to the saturation of the overburden mass and resulting in a landslide. These areas comprise coal shale, which decomposes into heavy loam and clay when saturated, forming the mudflow. The significant movement of soils in March 2018 to the surface of an already backfilled soil mass, together with substantial watering of the massif from both the base (backfilled stream) and the surface (snow melt), initiated the mudflow. The cause is the development of a water-coal slurry within the technogenic soil massifs.

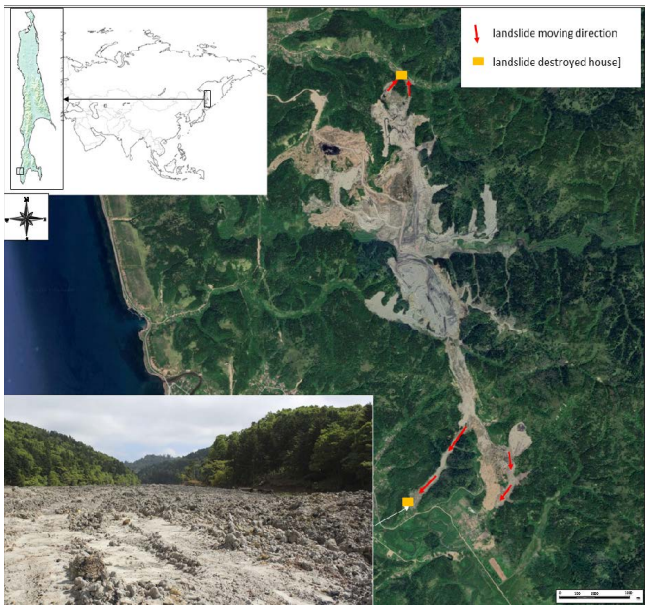


Figure 2: Mudflows formed from the soils of the Lopatinsky-Vostochny overburden dump of the Gornozavodsky brown-coal deposit in the village of Gornozavodsk, Nevelsk district (Southwestern coast of Sakhalin Island).

Coal dust particles, with a fine-dispersed composition ranging from 50 to 300 microns and a negative charge, exhibit pronounced colloidal properties, actively bind water and form stable water-coal suspensions. Such suspensions have a saturated consistency (up to 70%) and display pseudo-plasticity, where the viscosity decreases with increasing velocity.

Mudflows formed on waste rock dumps and coal mine tailings exhibit features typical of nival-type landslides. The formation mechanism can classify these landslides as extrusion, shear, or liquefaction. Landslide masses move at low velocities (up to 2-4 m/s) and have a significant velocity gradient throughout the flow depth. The decomposition of water-coal suspensions within landslide masses occurs primarily not through sedimentation (settling) but through desiccation.

Another example is the frequent landslides in Kholmsk city and the surrounding district on the southwest coast of Sakhalin Island. Kholmsk lies within a landslide zone (Figure 3), where landslides occur nearly yearly. Moreover, landslide occurrences have risen due to the technogenic impact on the city's natural environment.



Figure 3: Landslide boundary and movement direction in the city of Kholmsk.

In picture Figure 4, mudflows from the storage of construction soils in the channel of a small watercourse in 1978 destroyed several private homes and damaged the building of a medical facility in Kholmsk.



Figure 4: Deposition of a technogenic mudflow resulting from the storage of construction soils in the creek valley in Kholmsk, 1978.

From August 8 to 12, 2010, 145.3 mm of liquid precipitation fell in Kholmsk, exceeding the monthly norm of 100 mm. The daily maximum rainfall reached 125 mm on August 11, leading to the registration of 16 mudflows in the Kholmsk district, six of which occurred within Kholmsk itself. Notably, the mass manifestation of mudflows in Kholmsk was attributed to human activity, including uncontrolled storage of construction materials in the headwaters of small streams, the accumulation of household waste in residential areas adjacent to these streams, and the delayed maintenance of storm sewers and drainage systems along the city streets and railway.

The largest of the registered mudflows in Kholmsk passed through the left tributary of the Tatarka river and discharged in the area of the city clinical hospital on Shevchenko street. The discharge cone of this debris flow was intermittent and predominantly consisted of household and construction debris, which blocked part of the hospital's territory and the driveways between the garages. The accumulation of construction soil without drainage measures and consideration of the geological structure of the Kholmsk territory led to the formation of an anthropogenic mudflow in the area of the complex of buildings of the Naval School at Makarov Street No. 1. The edge of the fill material triggered the landslide under the bend of the highway. Subsequently, due to a significant inflow of water since drainage from the roadway is not provided and the construction soil completely obstructs the channel of a small stream the landslide transformed into a mudflow, which travelled approximately 500 m and caused erosion of the ditch by the railroad near house number 70 on Chekhov street. The volume of deposits from this anthropogenic mudflow was around 500 m^3.

In Kholmsk, the discharge of mudflows into existing reservoirs significantly increased the suspended solids content of the water used for drinking purposes. A large portion of the city was without drinking water for several days. Thus, due to human activity, the mudflows intensified during the cyclone in August 2010. Such soil deposits in an unstable equilibrium state become mobilized when liquefied or eroded by temporary water flows (from heavy rains, snowmelt, and other factors), resulting in landslides and mudflows.

On April 15-16, 2018, a landslide occurred on the southwest coast of Sakhalin Island (Yuzhno-Kamyshovy Ridge), affecting a section of the Yuzhno-Sakhalinsk-Kholmsk highway, which is of regional and federal importance, near the Kholmsk household waste dump. A combination of natural and anthropogenic factors leads to the active occurrence and development of landslide processes in the area road.

The landslide occurred in the old trough filled with artificial soils during the road's reconstruction in the mid-90's. The erosion-denudation trench and the ancient landslide trench on the slope were also backfilled with artificial soils for many years, resulting in unstable technogenic soil masses within the backfilled trenches. Meanwhile, numerous temporary and permanent shallow watercourses were backfilled, leading to the constant saturation of anthropogenic and natural soils on the slope, decreasing their stability. The road in the mid-90's of the twentieth century laid the surface of the soil massif. Landslide processes were activated in 2018 due to the watering of the soil massif. According to Savarensky's classification, this follows the mechanism of consequential block landslides. The sliding surfaces of the landslide align with the contacts between rock strata, groundwater horizons, and watered soil horizons. The total volume of rocks in the landslide body is approximately 50,000 m^3, with depths ranging from 1.5 to 18.0 m. The landslide features cracks and subsidence steps marked on the surface of the massif (Figure 5).

A landslide damaged the roadway, and its movement continues to this day. The stability of the landslide massif has been impacted by the load from the roadbed and moving transport on the surface of the array of artificial soils, the infiltration of surface and atmospheric waters into the soil massif, undercutting at the foot of the soil massif during the highway reconstruction, and the movement of solid waste located at the foot of the slope.



Figure 5: Landslide on the section of the road between Yuzhno-Sakhalinsk and Kholmsk. Yuzhno-Sakhalinsk - Kholmsk in the area of the household waste landfill (Kholmsk, southwest coast of Sakhalin Island), 2018 and the geological column of the well in the landslide body.

In addition to landslides and debris flows, snow avalanches occur on the slopes of dumps, excavations, and quarries (Figure 6). Creating artificial slopes increases the area exposed to avalanche processes, complicating farming and heightening the avalanche hazard for the population. Although artificial avalanches typically have low relative flow heights and rarely exceed a volume of 1,000 m^3, they have consistently caused economic damage and human casualties. Under conditions of urbanization, small snow avalanches on artificial slopes often involve children.



Figure 6: Snow avalanche caused by slope undercutting during road construction.

Numerous incidents of individuals caught in avalanches from artificially created slopes have been documented in the Russian Federation. For instance, in 2008, in the Bugulma settlement (Republic of Tatarstan), an avalanche from a railway embankment only 20 meters high resulted in nine people being buried, four of whom lost their lives.

RESULTS AND DISCUSSION

Slopes of railway and road embankments, various excavations, pit berms, snow dump slopes, soil, rocks, and debris contribute to the formation of dangerous exogenous geological processes such as landslides, mudflows, and avalanches. When planning anthropogenic activities, particularly in mountainous regions, it is crucial to consider the specifics underlying the formation of these processes to minimize risks to populations and economies. Therefore, evaluating the type and degree of anthropogenic activity's influence on the formation and activation of hazardous slope gravity processes is essential. We have identified types of anthropogenic activities that alter the parameters of these dangerous slope processes. The most common human activities that affect these parameters (mudslides, landslides, avalanches) manifest in specific impacts on natural landscapes.

Changes in the area's forest cover whether due to deforestation, forest plantations, fires, or other factors impact snow avalanche paths, mudflow basin watersheds, and landslide slopes. Deforestation within watershed boundaries, even without significant soil and vegetation cover destruction during harvests or caused by forest fires, results in increased surface runoff and, consequently, a higher volume of the water component in mudflows. Surface runoff increases by 1% for small mountain rivers and 2% for small mountain stream watersheds when forested areas are reduced by 10%. This leads to the intensified development of various exogenous geological processes on the exposed mountain slopes, activating mudflows.

Removing forests along avalanche paths increases the frequency of snow avalanches, while areas of wind-driven snow transport lead to the formation of new large snow cornices. In contrast, forest plantations serve as a control measure for snow avalanches.

Changing the type of underlying surface (destruction of soil and vegetation cover on slopes, plowing slopes). When the soil and vegetation cover are destroyed, the surface runoff may decrease (if friable clastic or highly fractured rocks are present) or increase (if rocky, poorly permeable soils are present), depending on the weathering crust of the rocks. Landslide and mudflow processes become active when surface runoff decreases due to rising soil humidity. In contrast, erosion processes activate when surface runoff increases and non-washing speed rises in channels of disconnected soils. Alterations to the underlying surface characteristics along avalanche paths result in a higher avalanche rate; additionally, changes in the traction between the snowpack and the underlying surface influence the frequency of avalanche occurrences.

Improper agricultural technology techniques, mainly longitudinal plowing on slopes, contribute to the creation of furrows, which serve as centers of erosion. This practice also significantly worsens mountain slope surface degradation and facilitates mudflow formation.

Relief reshaping (including excavation, installation, undercutting, dumping, quarries, etc.) When snow avalanches descend from the slopes of artificially shaped reliefs, alterations in the slope's morphology and morphometry affect the avalanche's dynamic characteristics, including flow velocity, initial consolidation pressure, friction parameters, and an avalanche path.

In many cases, undercutting the lower part of the slopes during road construction triggers rock slide, creep, and slump processes, which can supply debris for mudflows. Improper placement of these or other construction objects creates obstacles in the mudflow transit zone. Their location, size, and design significantly alter mudflow dynamics and scale (flow velocity, height, deposit volume), consequently increasing damage caused by mudflows.

Landfills on the slopes of stream valleys and household waste storage in small stream beds also pose obstacles in the mudflow transit zone. These soil dumps, which exist in an unstable state of equilibrium, typically move when liquefied or eroded by floodwaters (from heavy rains, snowmelt, and other causes), resulting in mudflows.

Various human activities can be categorized based on the degree and nature of the anthropogenic factors that affect the parameters of hazardous slope gravity processes. There are three primary stages.

- Formation-developing completely artificial construction aggregates (such as embankments, snow dumps, soil, garbage, quarries, dams, channels, excavations, and pits for snow avalanche protection).
- **Transformation:** This directly impacts natural complexes of landslides, mudflows, and snow avalanches, where human activity alters the characteristics of hazardous slope processes.
- **Indirect impact:** Engaging in human activities in areas near landslides, mudflows, and avalanches changes the characteristics of hazardous slope processes.

Changes in the characteristics of dangerous slope processes influence the parameters of the type of impact, which determine the nature and extent of their effects on the population and local economy. Such parameters for debris flow and landslide processes include the spatial percentage of affected areas, dynamic characteristics, formation frequency, and volumes. Additionally, human activity can affect the activation of dangerous slope processes (Table 1).

Table 1: Changes in the parameters of snow avalanche, mudflow and landslide processes result from various anthropogenic activities.

Anthropogenic activities		Characteristics affecting process parameters	Parameters of hazardous slope processes		
Group	**Subgroup**		**Snow avalanche processes**	**Mudflow processes**	**Landslide processes**
Formation	Creating positive and negative landforms	Change in the number of avalanche, mudflow and landslide massifs	Change in area affected	Change in area affected	Change in area affected
Transformation	Transformation of the underlying surface	Changes in surface roughness, the type of snow metamorphism, the rate of rock weathering, and the mode and rate of rock wetting	Changes in the dynamic characteristics of snow avalanches	Changes in the dynamic characteristics of mudflows	-
	Landform transformation	Changes in slope gradient, elevation, slope area and profile	Change in shaping frequency, change in dynamic characteristics, change in volume	Change in shaping frequency, change in dynamic characteristics, change in volume	Volume change; change in dynamic characteristics; activation or stabilization of the process
	Transforming vegetation cover	Changes in surface roughness, the type of snow metamorphism, the rate of rock weathering, and the mode and rate of rock wetting; changes in wind speed and direction	Change in shaping frequency, change in dynamic characteristics, change in volume	Change in shaping frequency, change in dynamic characteristics, change in volume	Change in shaping frequency
	Hydrological transformation	Changes in the type of snow metamorphism	Change in dynamic characteristics	Change in shaping frequency, change in dynamic	Activation or stabilization of the process

		and the mode and rate of rock wetting		characteristics, change in volume	
Indirect impact	Surface transformation in the wind transport zone	Changes in wind speed and direction, the mode and rate of rock wetting	Change in shaping frequency, change in dynamic characteristics, change in volume	Change in shaping frequency, change in dynamic characteristics, change in volume	Activation or stabilization of the process
	Dusting	Decrease in surface albedo	Change in shaping frequency (avalanche patterns)	Change in shaping frequency	Change in shaping frequency
	Shockwave impact	Decompaction of bedrock or engineering soil strata and snow stratification	Activation of avalanche processes	Activation of mudflow processes	Activation of landslide processes

An example of the formation of a new mudflow complex is the Lystvenichny quarry dump, an artificial mudflow discussed in this paper when describing the cases in Figure 7. This figure illustrates the stages of anthropogenic debris flow formation, ranging from the accumulation of clastic material in the upstream portion of the stream basin, represented by rock dumps, to its descent and debris deposits in the stream channel. Before the quarry operation, no mudflow processes were observed in this stream.

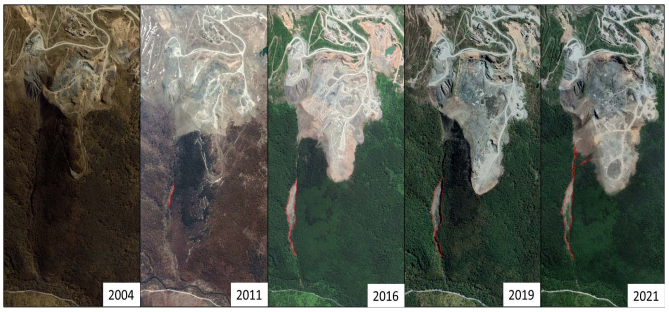


Figure 7: Formation of anthropogenic mudflow complex in the basin of the unnamed creek (slope of Medica, Susunai Ridge, Sakhalin Island) (mudflow deposits are outlined in red).

Beyond the adverse effects on the natural environment, which involve increased instances of slope processes and associated damage, there are also positive initiatives to mitigate snow avalanches, mudflows, and landslide activity. The alteration of the vegetation cover (Table 1) may involve constructing avalanche protection structures and establishing forest plantations in avalanche-prone areas, ultimately contributing to avalanche prevention (Figure 8). An avalanche from the slope of Jambul caused damage to a sanatorium building in 1965, leading to the decision to design avalanche protection structures on the hill. By 2012, the frequency of avalanches had reduced from once a year to 3-5 times annually, and as of that date, no avalanches reaching the foot of the slope have been recorded.

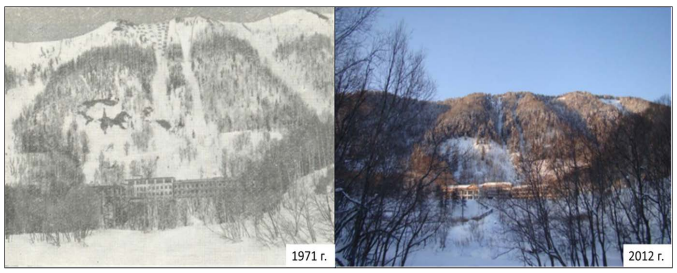


Figure 8: Avalanche path in Dzhambul (eastern spurs of the West Sakhalin Mountains, southern Sakhalin) following the construction of avalanche protection structures after 40 years.

An example of a negative indirect effect on snowpack due to increased avalanches is a surface transformation in the wind transport zone, which affects vegetation cover and the development or destruction of buildings and structures. It influences adjacent relief components, meaning any activity that alters the wind regime. The dust emissions discussed in this work refer to the settling of delicate particulate matter on snow, vegetation, and soil surfaces. Additionally, the shock-wave effect on the snowpack and frozen or unfrozen bottom soils is caused by heavy machinery, mining activities involving explosions, and mechanisms that generate shock waves.

We also need to recognize that only those local economic activities capable of having a prolonged and large-scale impact on avalanche, mudflow, and landslide complexes have been identified. In avalanche forecasting, a "human avalanche" typically refers to an avalanche triggered by human activities such as skiing or snow biking. However, this phenomenon is challenging to predict and prevent; its large-scale impact means that the influence on the natural avalanche complex is localized, spontaneous, and short-term.

The varying degrees of anthropogenic activity on hazardous slope processes will depend, among other factors, on the zones of mudflow and landslide complexes (e.g., the starting zone, transit zone, or accumulation of mudflow or avalanche). For instance, reducing vegetation in the mudflow initiation zone will influence changes in the weathering rate and the mode and pace of soil wetting. Conversely, the loss of vegetation in the

transit and accumulation zones will not impact these processes but will determine the dynamic characteristics of the mudflow. This work does not include a classification of the nature and degree of anthropogenic activity based on the zones of the mudflow and landslide complex.

Our group and subgroup of anthropogenic activities are categorized based on their impact on avalanches, mudflow, and landslide complexes—from creating new complexes to activities in adjacent areas. Nevertheless, the scale of consequences resulting from indirect impact may be more significant than that of direct effects. It would be misleading to suggest that a new avalanche on the slope of a soil dump will lead to more negative consequences than deforestation in the zone of wind transport of an already avalanche-prone slope. Thus, the scale of consequences is determined by the extent of local economic activity. For this reason, our summary table does not provide quantitative indicators of the characteristics and parameters of avalanche, mudflow, and landslide processes.

The work lacks statistical analysis and numerical calculations of changes in the parameters of slope processes. This limitation is primarily due to the challenge of presenting a complete analysis of all the collected material on the slope processes discussed in this work within a single publication. Therefore, the table does not quantify the characteristics and parameters of snow avalanches, mudflows, and landslide processes. At this stage of the study, the authors have confined themselves to a qualitative description of anthropogenic activities and their consequences, which aligns with the stated primary objectives of this work. Conclusions regarding the impact of anthropogenic factors were based on many years of observations of avalanche, mudflow, and landslide processes in Sakhalin and other regions of the Russian Federation, as well as published data from other researchers. In the future, a classification for each hazardous slope process is planned to be developed separately.

CONCLUSION

After many years of research, the authors have gathered data on the formation of hazardous slope processes on Sakhalin (snow avalanches, mudflows, and landslides) triggered by anthropogenic factors. At all stages of local economic activity in this region, an increase in the occurrence of hazardous slope processes, either fully or partially instigated by human activities, was noted. The heightened strain on the natural environment and the corresponding rise in the frequency of anthropogenic and natural-anthropogenic mudflows, landslides, and snow avalanches have underscored the necessity to systematize human activities and the consequences of the processes addressed in this study.

The authors proposed a classification of human activities based on the nature of the influence of the anthropogenic factor on the formation of mudflows, landslides, and snow avalanches. Due to the impact of nearly all types of human activity on natural avalanches, mudflow, and landslide complexes, these can be divided into direct and indirect effects. Direct impact, depending on the extent of change in the natural environment, can further be classified into two categories: The creation of a new, previously non-existent avalanche, mudflow, or landslide complex, or conversely, the destruction, alteration, or transformation of an already existing natural avalanche, mudflow, or landslide complex due to direct impact within it.

Thus, three anthropogenic activities are identified based on their influence on avalanche, mudflow, and landslide processes: Formation, transformation, and indirect impact. We identified possible anthropogenic activities, characteristics of hazardous slope processes, and parameters of these processes that change due to anthropogenic influence. The proposed systematization and classification enable the planning and development of economic activities to evaluate the consequences for the local population and economy stemming from potential activation and changes in the characteristics of hazardous slope processes.

The authors recommend using this classification both during the pre-project phase of engineering-geological surveys and throughout the construction stage of buildings and structures when it is essential to evaluate changes in engineering-geological conditions, the emergence of hazardous geological processes, and the factors influenced by the economic development of the area. Monitoring dangerous slope processes to establish preventive measures against their occurrence is essential. For instance, when planning a rock dump or tailings based on the suggested classification, one can promptly plan measures to prevent the formation of slope processes or delineate any new avalanche or landslide complexes on the hazard mapping.

ACKNOWLEDGEMENT

Thank you to the FGBUN Special Design Bureau for Marine Research of FEB RAS for providing help during the research and funds, which offered financial support for our research. The paper includes the results obtained within the FWWW-2024-0003 research project of the Special Research Bureau for Automation of Marine Research FEB RAS.

CONFLICT OF INTEREST

No conflict of interest exists. We wish to confirm that this publication is not associated with any known conflicts of interest and that no significant financial support for this work could have influenced its outcome.

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