Natural and anthropogenic risks after a giant landslide in the Russian Far East

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Abstract. At the Bureiskoe Reservoir (Far East, Russia) in December 2018 at a temperature of 36°C below zero the giant landslide is occurred. Landslide with a total volume of 24.5 million m³ blocked the reservoir from one shore to the opposite one, disrupting the access of water to a large hydroelectric power station downstream. Blasting operations were carried out with the use of trinitrotoluene and hexogen to revive the water flow. As a result of the landslide natural hazards (direct impact of the landslide, and tsunami) were happened, and the further strong impact was caused by humans (blasting). Volatile organic compounds (VOCs) and elemental composition were accepted as the main indicators of water quality. Parameters of these indicators varied at different near-shore sites above and below the landslide area. More significant changes are recorded after blasting operations. Hexane and toluene dominated the water passing the artificial channel. The genesis of VOCs can be associated with the biogeochemical processes of methanogenesis, methanotrophy, and the detonation products of explosives. Mercury, methanol, toluene, and xylenes in water samples were detected. This is evidence of the presence of a prerequisite for the formation of toxic methylmercury, a risk factor for aquatic biota.

1. Introduction

According to the latest data, the most common risk factors leading to loss of life are avalanches (37%), lightning (16%), floods (12%), hurricanes (10%), rockfalls (8%), landslides (7%), and other processes (9%). In addition to the main global factor – climate change, a significant portion of natural disasters is associated with economic development, anthropogenic changes in landscapes, river channels, and transformation of underground space [1]. In regions with a wide range of temperature changes, studies of the behaviour of frozen soils under various objects, including highways and reservoirs, become relevant. Among the many geological and physicochemical processes, special attention is paid to the study of the degeneration of permafrost, soil mobility when the temperature regime changes [2]. Cryogenic landslides often occur in Alaska, northern Canada, and Central Yamal (Russia). With an increase in the thawing depth of permafrost, it is assumed that cryogenic landslides will intensify in northern regions [3]. The destructive effect increases with a wide range of winter and summer temperatures and with regular processes of freezing and thawing of water in the pore space of rocks [4].

It has been established that melting of permafrost occurs at temperatures from −1.8°C to 0°C and is accompanied by the emission of huge volumes of methane into the atmosphere [5]. Explosive gas emission in a short period is associated with cryogenic processes and called “cryogenic volcanism”. The effect is increased by the sharp freezing of water in the pore space [6]. The study of the rocks' destruction mechanisms as a result of freezing-thawing is important for preventing the destruction of infrastructure buildings in cold regions [7]. The risk of methane release is increased as a result of
sporadic sharp thawing events with the formation of voids, compared with slow thawing and gradual subsidence of the surface horizons of frozen soils. Depending on soil moisture and oxygen saturation, mechanisms of transformation of accumulated in permafrost organic matters change and can be accompanied by the processes of methanogenesis and methanotrophy [8].

For the first time in the Russian Far East during the winter period (December 11, 2018), the giant landslide occurred with the movement of a large volume of rocks directly into the reservoir. The landslide dammed the former riverbed of the Bureya River from one shore to the opposite one, limiting the inflow of water to the reservoir of the Bureiskyaya hydroelectric power plant (HPP) [9]. On January 16, 2019, the water level difference in the riverbed above the landslide and below it in the area of the Bureiskyaya HPP reached 5 m. Massive blasting operations were carried out to solve the problem of flow restoration. About 260 tons of TNT (trinitrotoluene) were used for creating an artificial channel through the body of the landslide, and about 520 sets of shaped charges containing hexogen were detonated.

In the water area of the Bureiskoe Reservoir, there were two critical large-scale events associated with environmental risks. First, the landslide itself (entering into the water large amount of metamorphic rocks, crushed wood); secondly, blasting operations (additional crushing of rocks, the flow of detonation products of explosives, and triggering the water-rock interaction processes). After the landslide event, the first of all the concern about the social risk has arisen, namely probable flooding settlements and infrastructure systems (railways and power lines), as well as the threat to the operation of the Bureiskyaya HPP. Along with the current social risk, prolonged environmental risks are prominent too. Recognizing and preventing them is an extremely complicated task. In addition to the landslide itself, this caused the entry of crushed rocks into the aquatic environment, TNT and hexogen explosives and their detonation products act as additional sources of risks for soil, rocks, and water pollution.

The manuscript presents data on the assessment of possible relationships between the content of volatile organic compounds (VOCs) and individual elements in water under the influence of natural (landslide) and anthropogenic (blasting operations) risks. This allows identifying the consequences of the use of explosives (TNT and hexogen) to restore the hydrological regime in the Bureiskoe Reservoir after a giant landslide in December 2018 in the Russian Far East.

2. Materials and Methods
The filling of the Bureiskoe reservoir was started in 2003. The width of the flooded channel of the Bureya River is 500-550 m, at a depth of 60-80 m. The transverse profile of the valley is asymmetric – the left bank is about 400 m high, steep with a slope of 30–35°. Before the flooding, the riverbed was pressed against the left bank and cut the base of the slope, constantly increasing the steepness and reducing its stability. The right slope of the valley is a gentle sloping terraced surface of erosion origin, more than 1 km wide and up to 50 m high above the current water level. Mouths of the tributaries are flooded and form narrow and deep bays 1.5-3.0 km long. Fluctuations in water levels in the reservoir between the maximum marks in early autumn and minimum in spring are 20 m. In the fault zones, increased fracturing of rocks was recorded, which significantly weakened the stability of the slope, preparing the displacement of huge masses of rocks [9]. The catchment area of the Bureiskoe Reservoir is located on a territory with very difficult permafrost-hydrogeological conditions, most of which is confined to the area of development of insular, discontinuous, and continuous permafrost. The migration of metals in coal-bearing and permafrost rocks is influenced by the presence of methane and its conversion products.

On December 11, 2018, at 14:48 local time at the air temperature of 36.2°C below zero, the landslide occurred on the Bureiskoe Reservoir. According to hydrological and geodetic measurements, the volume of the landslide was 24.5 million m³. The volume of the surface part of the landslide exceeds 4.5 million m³; the main part of it is under the water. The depth of the Bureiskoe Reservoir at the site of the landslide event is more than 70 m [10]. Other landslide body parameters are as follows: length is 800 m from edge to edge; height is above the reservoir edge from 7.5 to 46 m. The landslide should be assessed as a unique natural event because usually similar phenomena in the Russian Far East occur in the summer, but not in winter. Due to the
inaccessibility of the area where the landslide occurred, research was carried out during short-term helicopter flights of the Ministry of Emergency Situations of Russia. Water samples were taken above and below the landslide body near the left and right banks. After the blasting operations, water samples were taken from the formed channel from the flat bank (figure 1).

The elemental composition of natural waters was determined by inductively coupled plasma mass spectrometry on an ICP-MS ELAN-9000 (Perkin Elmer, USA). Determination of the content of volatile organic compounds (VOCs) in water samples was carried out by gas chromatography with the use of an HP-FFAP column (50 m; 0.320 mm; 0.50 microns) at a temperature range of 45-200°C.

3. Results and discussion
After the landslide, significant changes in the coastal landscape took place: the destruction of rocks and a unique event – a river tsunami. The wave hit the opposite densely forested sloping bank then moved up the slope by 1 km, reaching a height of about 56 m above the water edge in the reservoir [9]. The water flow broke tree trunks, leaving shattered stumps up to one meter high. A general view of the landslide body, the area of the destroyed forest, and the artificial channel after blasting operations, is shown in a photo taken in April 2019 from a drone (figure 2).
3.1. Composition of Volatile Organic Compounds after the landslide

It is known that alkanes (methane, ethane, propane, butane, and hexane) are widespread in sedimentary rocks, oil fields, coal beds, and swamps. As a result of the microbiological transformation of alkanes, various VOCs are formed [11]. The qualitative and quantitative composition of VOCs in the water of the Bureiskoe Reservoir before the start of blasting operations was significantly discrepant on different sites above and below the landslide body (table 1).

| Site | Hexane | Acetone | Methanol | Toluene | m-xylene |
|------|--------|---------|----------|---------|----------|
| 1    | nd     | 0.018   | 0.13     | 0.001   | 0.001    |
| 2    | nd     | 0.009   | 0.05     | 0.001   | nd       |
| 3    | nd     | 0.14    | 0.07     | 0.001   | 0.014    |
| 4    | nd     | 0.03    | 0.09     | 0.001   | 0.095    |
| 5    | 0.008  | 0.04    | 0.23     | 0.001   | 0.001    |
| 6    | 0.41   | 0.03    | 0.18     | 0.004   | 0.004    |
| 7    | 0.66   | 0.05    | 0.49     | 0.054   | 0.014    |
| 8    | 2.73   | 0.10    | 0.39     | 0.006   | 0.016    |
| 9    | C1 /14.02 | nd | 0.02 | 0.06 | 0.001 | nd |
| 10   | C2/14.02 | nd | 0.025 | nd | 0.001 | 0.018 |
| 11   | C3/14.02 | 1.3 | 0.06 | 0.07 | 0.01 | 0.05 |
| 12   | C4/14.02 | 0.06 | 0.03 | 0.22 | 0.43 | 0.001 |
| 13   | C5/1.03 | 0.005 | 0.005 | 0.04 | 0.002 | nd |
| 14   | C6/1.04 | 0.007 | 0.024 | nd | 0.001 | 0.001 |

* Lb – Left bank; Rb – Right bank; nd – not determined.

This may be due to the slow drainage of water through the landslide body and the influx of organic matters from the soils and pore space of rocks. Methanol was the dominant component in all water samples. High concentrations of methanol were detected in water samples near right shore sites below the landslide body due to wood remnants flooding after the tsunami. Above the landslide body near the right bank, the maximum content of acetone was found in the water, 14 times higher than that near the left bank. Fluctuations in the water level in the reservoir (20–40 m) contribute to the release of groundwater, which takes part in the formation of aufeis (Auf). The composition of organic matter in natural aufeis is formed under the influence of cryo- and biogeochemical processes and reflects the interaction of groundwater with rocks, soils, wood, or peat bogs.

The melts of aufeis samples differed significantly in colour and VOCs composition (table 1). Thus, hexane, methanol, ethyl-, butyl acetate, and butanol were present in transparent water from the melted ice (Auf-1). In the turbid water samples from the melted ice (Auf-2), higher concentrations of methanol and toluene, as well as maximum concentrations of isobutanol and isopropyl benzene, are recorded. The richest organic matter (OM) composition was characteristic of brown ice (Auf-3). It was formed under the influence of the interaction of groundwater with soils and wood remnants. This sample was the only contained benzene and its methylated isomers (p-, m-, o-xylene and toluene). The maximum concentration of hexane was recorded in it, the origin of which may be associated with the removal of low molecular weight VOCs by groundwater from fractured rocks and swampy areas. Since the samples of ice were taken before the start of blasting operations, the presence of hexane is not associated with the detonation products of hexogen.
3.2. Anthropogenic risks after blasting

From the point of view of environmental risks, entering the reservoir after blasting operations and involvement in biogeochemical processes a large volume of suspended solids is of great importance. Natural VOCs and detonation products of explosives (TNT and RDX) are inevitably present among the crushed rocks. In the landslide zone, there is a risk of pollution of the Bureiskoe Reservoir ecosystem by detonation products. Because of blasting, various gaseous carbon and nitrogen-containing components (CO$_2$, CO, O$_2$, H$_2$, CH$_4$; N$_2$, NH$_3$, C$_2$N$_2$, HCN, NO, N$_2$O; SO$_2$, H$_2$S, HCl, Cl$_2$), metal oxides, carbonates, cyanides, sulphates, chlorides, etc. are released. Environmental risk increases with the simultaneous intake of a large amount of detonation products (dinitrotoluene and nitrobenzene).

Water samples taken at different times from the channel, formed after blasting operations, differed in the composition of the VOCs depending on the content of suspended matter. On February 14, 2019, 7 compounds were found in clear waters (sample C4/14.02), with a high content of methanol and toluene. The highest toluene content in water after blasting may well be associated with its anthropogenic origin.

Physical, chemical, and biological processes influence the potential hazard of explosives in the environment. Several explosives, including TNT and RDX, are biodegrading under aerobic and anaerobic conditions [12]. Although toluene is the end product of the anaerobic decomposition of TNT [13]. The high degree of environmental risk is posed by water-soluble explosives, which have a toxic effect on fish and mussels directly through the aquatic environment [14]. Persistent TNT metabolites have been found in Atlantic salmon muscle tissue [15]. Studies have shown prolonged risks following the use of explosive mixtures. It increases the degree of environmental risk after blasting operations at the Bureiskoe Reservoir.

3.3. Elemental composition change

Landslide on the Bureiskoe Reservoir contributed to the formation of a biogeochemical barrier, which significantly changed the dynamics of many chemical elements migration. Elemental composition in water samples taken above and below the landslide body (near the left and right banks) differed significantly. This can be explained by the processes of water infiltration through the landslide body. Two groups were identified that differ in their behaviour. The first group consisted of elements which concentration increased below the landslide body: Al, Fe, W, Cr, and Pb; the second group consisted of elements, the concentration of which decreased: Mg, Ca, Zn, Se, and Cd. The most significant increase in concentrations at both banks below the landslide body was typical for Pb, and the minimum decrease was for Cd. On the right bank, where the vegetation was destroyed as a result of the tsunami, an increase in the concentration of Ni and Cu was recorded (figure 3).

![Figure 3. Content of elements (μg/L) in water samples in the landslide area: 1-4 (01.25.2018) – above and below the landslide body; 5-10 – water from the channel, after blasting: 5-8 – 02.14.2019; 9 – 01.03.2019; 10 – 17.04.2019.](image-url)
Such quantitative changes in the elemental composition of water in the Bureiskoe Reservoir are caused by many factors: the influx of OM and lithogenic elements from rocks, plant, and soil residues into the surface waters; the interaction of water with organic-and-mineral complexes; by changing the redox potential, which affects the solubility and migration ability of toxic heavy metals.

After the blasting operations, a sharp decrease in the content of iron and aluminium was recorded and its partial recovery in March (figure 3). This behaviour can be associated with the presence of OM. Thus, in water samples taken on February 14, 2019, a wide variety of organic compounds of various structures was found, including hexane, acetaldehyde, ethyl acetate, m- and o-xylens, etc. According to the correlation analysis, a positive relationship was revealed in the vapours Fe-hexane and Fe-isopropylbenzene (R = 0.952 and R = 0.658, respectively). This may be due to the extraction of humic substances from the pore space of finely dispersed rocks that entered the water after explosions and their interaction with the dissolved form of iron. Manganese content decreased both after passing through the landslide body and after blasting operations when a large amount of suspended material was present in the channel. Changes in the concentration of zinc and chromium were less pronounced. The copper content after blasting operations took a long time to recover. This behaviour of copper can be associated with the presence of methanol in the aqueous medium. In water samples taken in the channel after the restoration of flow through the landslide body, the content of iron, manganese, aluminium, copper, and zinc did not reach the concentrations established before the blasting operations. Only the concentration of chromium increased 2.3 times after blasting. Direct positive correlations have been revealed between pairs of elements Fe-Al, Al-Cu, Zn-Cu (R = 0.933; R = 0.919; R = 0.900, respectively).

Blasting operations have led to a sharp increase in the content of toxic elements Pb, Cd, and Hg. Moreover, the concentrations of lead and mercury in the channel exceeded the values established before the explosions (Pb is more than 7 times, Hg is 80 times). Increased mercury concentrations (0.08 μg/L) were found in water samples taken in the channel immediately after the end of blasting, which decreased in April to the detection limits (<0.001 μg/L). Such features of the distribution of this metalloid are associated with the supply of fine soil particles and crushed rocks. The presence of mercury and methyl-containing OM (toluene, m-, o-xylens) in water samples is a prerequisite for the formation of its soluble methylated form (CH₃Hg⁺). Methylmercury is the most toxic form, which is formed in the presence of methyl radicals in the environment [16]. In our case, both natural methyl-containing OM and the transformation products of trinitrotoluene could affect the mobility of mercury. Bioaccumulation of methylmercury increases the degree of ecological risk to aquatic organisms.

4. Conclusions
After the landslide, two critical events took place on the Bureiskoe Reservoir, associated with risks: natural (landslide, river tsunami) and anthropogenic (blasting operations). The environmental risk factors that influenced the water quality in the Bureiskoe Reservoir after a giant landslide were:

- release from the pore space the OM associated with the cycle of methane and lithogenic elements in the course of water infiltration through the landslide body;
- destruction of forests as a result of the tsunami, the entry of OM from soils and crushed wood into the water;
- blasting operations, which intensified the processes of interaction between soils and rocks, the flow of charred wood, decomposition products, and input of detonation products of explosives to ecosystems.

Prolonged environmental risks are associated with surface runoff during spring snowmelt and summer floods, crushed rocks, soil particles, and sedimentation of pollutants at the bottom of the reservoir. They can provoke the concentration rise of methylated compounds and toxic elements in the water around the landslide. The remains of trees on the shores of the reservoir after the tsunami and settled in shallow waters can cause an increase in the colour of water and an increase in the concentration of high molecular weight OM.
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