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WATER
MICROBIOLOGY

Change in Abundance and Activity of Microbocenoses in the Area of Influence of a Large Landslide at the Bureya Reservoir

L. M. Kondratyeva[a], **Z. N. Litvinenko**[a], **D. V. Andreeva**[a], *, and **A. S. Bashkurova**[b]

[a] *Institute of Water and Ecology Problems, Far East Branch, Russian Academy of Sciences, Khabarovsk, Russia*

[b] *Institute of Mining, Far East Branch, Russian Academy of Sciences, Khabarovsk, Russia*

**e-mail: freckles2008@yandex.ru*

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Abstract—The results of field and experimental microbiological studies of water, soil, and rock samples in the influence zone of large landslide are presented. The landslide occurred in December 2018 and blocked the Bureya Reservoir from coast to coast. An artificial channel was created to restore the hydrological regime with the use of TNT (trinitrotoluene) and RDX (hexogen). A comparative analysis of the abundance of cultivated heterotrophic bacteria around the landslide body and in the artificial channel is carried out. The activity of microbial communities in relation to easily available (peptone, lactate, and starch) and difficult-to-mineralize humic compounds is also determined. With the use of spectrometry and gas chromatography, it is shown that an increase in the diversity of aromatic compounds in water is accompanied by an increase in the abundance of heterotrophic bacteria. A number of toxic substances, including methanol and methylated benzene derivatives, are found among the dominant components in the water. Its concentrations increased after the water drained through the landslide body and after imploding works. Many of the volatile organic compounds may have been products of microbial metabolism when water interacts with rocks. A hypothesis on the role of methanotrophic and methylotrophic bacteria in the genesis of methanol and toluene is discussed.

Keywords: microbial communities, Bureyskoye Reservoir, landslide, volatile compounds, trinitrotoluene, hexogen

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INTRODUCTION

Landslides are widespread in regions with rugged terrain; in mountains; and on the steep banks of rivers, reservoirs, and seas (Andres and Badoux, 2018). In Russia, landslides occur in the North Caucasus, the Urals, the Volga region, Eastern Siberia, Primorye, on the banks of the Don and Kuban rivers, Sakhalin Island, and Kola and Kamchatka peninsulas. It was shown using the example of the Krasnoyarsk Reservoir that the rate of landslide displacement depends on the intensity of disintegration of rocks at the base of landslide blocks and the formation of clay material capable of plastic deformation (Kozyreva et al., 2015). Landslide processes are most often considered from a geological and physical point of view. In some cases, the destruction of rocks on the slopes is considered a result of chemical erosion due to freezing–thawing (Zhang et al., 2017; Qu et al., 2018). However, landslides change the dynamics of biogeochemical processes in soils and aquatic environments, which can be accompanied by structural transformations in biocenoses. Environmental problems associated with water pollution and possible consequences for aquatic organisms are extremely rare taken into account.

In December 2018, a large landslide occurred for the first time in the Far East, falling directly into the Bureya Reservoir. The filling of the reservoir of the Bureya HPP started in 2003. The peculiarities of the construction of hydroelectric power plants in the Far East are associated with the harsh climatic conditions and the spread of permafrost. The near-dam and central parts of the Bureya Reservoir are located in an area of insular distribution of permafrost. Permafrost islands are confined to the loams lying on the surface and overlying peat bogs. In loose sediments, permafrost is located no deeper than 12 m; under oxbows and small watercourses, the permafrost boundary drops to 6–7 m (*Nauchnye* ..., 2005).

According to the project, fluctuations in the water level in the reservoir are 20 m. As a result, wide and flat areas periodically fall into the flooding and drainage zone. The activation of exogenous geological processes (landslides, avalanches, taluses, waterlogging, kurums, heaving mounds, thermokarst, etc.) was predicted when the reservoir was filled up to the design level by means of cyclic flooding and drainage. It was

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Abbreviations: CHB – cultivated heterotrophic bacteria; CFU/mL – Colony Forming Unit; MC – microbial community; OCs – organic compounds; HNa – sodium humate.

assumed that the amount of reworking of coastal slopes can be from 5 to 15 m in the first 10 years, and then it can reach of 40 to 50 m (*Nauchnye* ..., 2005).

In the first years the Bureya Reservoir was filled, a slowdown in water exchange, temperature regime, features of forest cutting on the banks, accumulation of plant residues in bottom sediments, a decrease in self-cleaning ability, and the excessive development of blue-green algae were the main negative factors affecting the change in the quality of natural waters (*Gidroekologicheskii* ..., 2007).

An uneven distribution of dissolved and suspended organic matter supplied with surface runoff from flooded soils and plant residues during the formation of the reservoir ecosystem led to a change in the number of microorganisms–destructors in water at different sections. High-quality deforestation was carried out in front of the dam (the first section). The infrastructure of the hydroelectric power station and the road are located on the right bank. The reservoir was filled at a distance of 8 km from the dam (the second section), despite incomplete deforestation (trees were flooded at the root; timber was not transported). A bioindication based on determining the number of cultivated heterotrophic bacteria (CHB) and their activity in relation to various groups of organic compounds (OCs) was one of the methods for assessing the quality of water in the reservoir (Kondratyeva and Chukhlebova, 2005). In the summer of 2003, the CHB number at the first section near the left flat bank in the surface water layer was 9.2×10^2 CFU/ mL, while near the right bank it was 10 times higher (110×10^2 CFU/mL). At the second section, the CHB number near the left bank among the timber flooded at the root reached 13×10^2 CFU/mL; at the right bank it was 65×10^2 CFU/mL. In October, after intense rains, the number of the CHB increased at both sections. In the front of the dam, it was comparable at both banks ($\sim 160 \times 10^2$ CFU/mL), while below the dam it increased to 360×10^2 CFU/mL at the left bank and 289×10^2 CFU/mL at the right one.

Despite forecasts about the possibility of exogenous geological processes in the zone of influence of the Bureya Reservoir, the giant landslide in December was a surprise. Due to the landslide, blocking the reservoir from coast to coast, there was a threat to the operation of the Bureya HPS and flooding of settlements located upstream (Makhinov et al., 2019). To restore the flow in the reservoir, it was decided to create an artificial channel in the body of the landslide by carrying out large-scale blasting operations. According to the Russian Ministry of Defense, about 260 t of TNT (trinitrotoluene) was used and about 520 sets of shaped charges containing RDX (hexogen) were blown up to create this channel.

Due to the landslide and the following tsunami, a large volume of crushed metamorphosed rocks and shattered wood entered the aquatic environment of the Bureya Reservoir (Makhinov et al., 2019). After blasting operations, the explosives trinitrotoluene and hexogen were additional sources of environmental pollution (water, soil, and rock). Among the products of their detonation, there are toxic 2,4-dinitrotoluene and 4-aminodinitrotoluene (Juhasz and Naidu, 2007; Won and Borden, 2016). These factors (landslide and blasting operations) influenced the water quality, structure, and activity of the reservoir microbial community (MC), providing its self-remediation potential.

Many microorganisms are capable of transforming trinitrotoluene under aerobic and anaerobic conditions, including bacteria from the genera *Pseudomonas*, *Enterobacter*, *Rhodococcus*, *Mycobacterium*, *Clostridium*, and *Desulfovibrio* and fungi *Phanerochate*, *Stropharia* (Serrano-González et al., 2018).

Although microorganisms are capable of degrading aromatic compounds, it has been shown that explosives and their decomposition products can have toxic effects. For example, for some anaerobic decomposers of aromatic compounds, effective concentrations leading to the inhibition of their growth by 50% were in the range of ~0.2 mM for ethylbenzene and xylene, ~0.5 mM for toluene, and 1.5 mM for benzene (Duldhardt et al., 2007). Under natural conditions in polluted water areas, these concentrations are higher; i.e., microorganisms that degrade aromatic compounds in situ can undergo a significant toxic impact (Tischer et al., 2013).

TNT and RDX are carcinogenic. It has been shown experimentally that aquatic organisms mainly accumulate the products of explosive transformation (Sims and Steevens, 2008; Strehse et al., 2017). The most dangerous are water-soluble products that have a toxic effect on fish and shellfish directly through the aquatic environment (Chatterjee et al., 2017). Regardless of the season, 4-amino-2.6-dinitrotoluene accumulates in mussel tissues (Appel et al., 2018). Persistent trinitrotoluene metabolites were detected in salmon muscle (Mariussen et al., 2018). The most dangerous are mixtures of explosives (Panz et al., 2013). For example, in a mixture of trinitrotoluene and hexogen, the decomposition time of detonation products can be from 6 to 600 days, depending on the particle size and physicochemical environmental conditions (Lever et al., 2005).

These examples show the long-term effects of explosives on aquatic life. The simultaneous flow of crushed rocks and detonation products of explosives into the Bureya Reservoir increases environmental risk for aquatic organisms. Microorganisms involved in the self-remediation of aquatic ecosystems can act as sensitive indicators of pollution.

When assessing the influence of environmental factors on landslide processes, special attention is paid to the response reactions of microorganisms developing in the micronishes of the pore space of rocks in the coastal zone. Different species of microorganisms are

Fig. 1. Site of landslide localization in Bureya Reservoir. Sentinel-2A space image (earth-chronicles.ru).

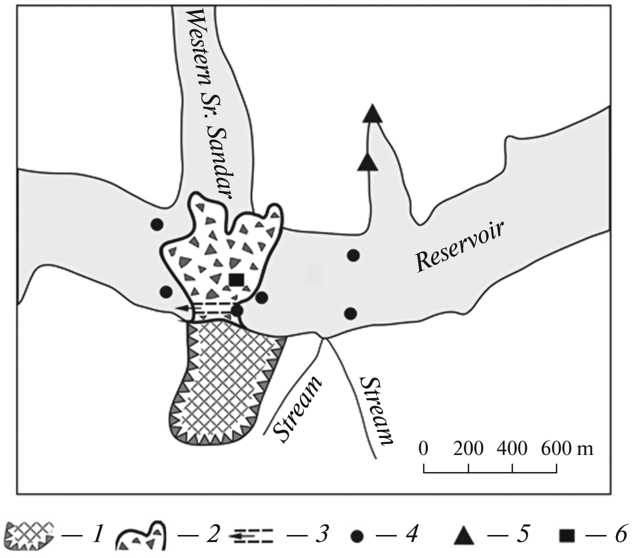

Fig. 2. Landslide boundaries and sampling sites: (*1*) landslide wall, (*2*) landslide body, (*3*) channel from the upper part of the reservoir to the lower part after blasting operations, (*4*) sites of water sampling, (*5*) sites of icing samples, and (*6*) sites of soil and rock sampling.

capable of forming biofilms, participating in the destruction or formation of minerals, as well as in the transformation and destruction of OCs. Evidence for a relationship between microbial communities and landslide formation was obtained (Błońska et al., 2018).

The goal of the present work was to determine the number of planktonic heterotrophic bacteria around the body of a large landslide and in an artificial channel after blasting operations on the Bureya Reservoir, study the activity of microbial communities of soil and crushed rocks in relation to different sources of carbon, and perform a comparative analysis of changes in the composition of volatile organic substances before and after blasting operations and to substantiate their genesis.

MATERIALS AND METHODS

In the landslide area on the Bureya Reservoir, the left bank is about 400 m high and steep, with a slope of 30°–35°. The right slope of the valley is a terracelike surface of erosion origin >1 km wide and ≤50 m high above the current level of the reservoir. The width of the flooded channel is 500 to 550 m, and the depth is 60 to 80 m. The mouths of the inflows form narrow and deep bays 1.5 to 3.0 km in length (Fig. 1). Fluctuations in the water level in the reservoir between the maximum in early autumn and minimum in spring are about 20 m.

The volume of the landslide is 24.5 million m^3, the above-water part being more 4.5 million m^3, but most of it is under water. The depth of the reservoir at the site of the landslide is more 70 m. The landslide is 800 m long and 7.5–46 m high (Makhinov et al., 2019). The filling of the reservoir played a significant role in creating the conditions for the displacement of the landslide, as it led to the penetration of groundwater under the base of the slope, which increased the water cut of fractured rocks in its lower part and reduced their stability (Kulakov et al., 2019).

Due to the inaccessibility of the landslide area, the studies in the water area of the Bureyskoye Reservoir were carried out during short-term flights of helicopters of the Ministry of Emergency Situations of the Russian Federation. Water samples were collected around the landslide and then (after blasting operations) from the channel formed in the landslide body (Fig. 2).

To assess the activity of MCs from different habitats in relation to easily accessible and difficult-to-mineralize OCs, we used water samples collected in the reservoir above and below the landslide body, icing (January 2019), water from an artificial channel (February and March, 2019), and 5-day water extracts of soil and rocks crushed by explosions. Extracts were prepared using 1 g of substrate and 100 mL of sterile distilled water.

The CHB number was determined using fish-peptone agar diluted 10 times and expressed in CFU/mL (Namsaraev et al., 2006). The potential activity of MC in relation to various carbon sources, including calcium lactate, peptone, yeast extract, starch, and sodium humate (HNa), was determined by the results of the cultivation at 20°C using M9 nutrient medium of the following composition (g/L of distilled water): KH_2PO_4 – 1.33, K_2HPO_4 – 2.67, NH_4Cl – 1, Na_2SO_4 – 2, KNO_3 – 2, $FeSO_4{\cdot}7H_2O$ – 0.001, $MgSO_4{\cdot}7H_2O$ – 0.1. Carbon sources were used in the following concentrations: calcium lactate, peptone, yeast extract, and starch 2 g/L; HNa 0.2 g/L. The growth of microorganisms on readily available substrates (biomass accumulation) was determined photometrically by the change in the optical density of the culture fluid using KFK-3-01 spectrophotometer at a wavelength of 600 nm.

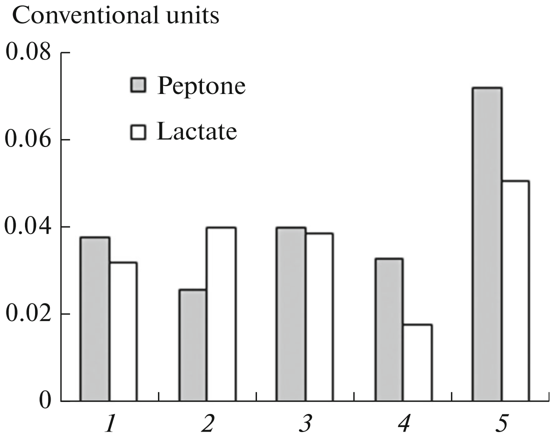

Fig. 3. Activity of planktonic heterotrophic bacteria when utilizing easily available substrates before (*1–3*) and after blasting operations (*4*, *5*). (*1*) Above landslide level at left bank; (*2*, *3*) below landslide level at left and right levels, respectively; (*4*) channel, February 14, 2019; and (*5*) channel, March 1, 2019.

The peculiarities of the microbial transformation of HNa were determined by the change in the values of the absorption of the culture fluid for 30 days at different wavelengths: the change in the total content of OC at $\lambda = 254$ nm, the presence of aromatic groups at $\lambda = 275$ nm (Kumar, 2006), and the transformation of chromophore groups responsible for the color of the aqueous medium at $\lambda = 436$ and 465 nm (Shirshova et al., 2015) using a SHIMADZU UV-3600 spectrophotometer (Japan).

The content of volatile OC in water samples from the reservoir and 5-day water extracts of different substrates (soil, crushed rocks after explosions) was determined by gas chromatography using an HP-FFAP column (50 m, 0.320 mm, and 0.50 μn) at a temperature range of 45 to 200°C.

RESULTS AND DISCUSSION

According to hydroecological monitoring data, during the filling of the Bureya Reservoir (2003–2007), the water quality according to hydrochemical, microbiological, and hydrobiological indicators differed significantly at different sections due to a change in the flow rate of water masses and the accumulation of plant detritus in the lower layers of water in front of the dam (*Gidroekologicheskii* ..., 2007). The intensive color of surface waters among trees flooded at the root was due to the decomposition of lignocellulose. This indicator was comparable with the color of water masses sampled in the bottom layers, where the transformation and destruction of plant residues occurred.

Taking into account that the composition and amount of OC utilizing by MC as carbon and energy sources have a significant effect on water quality, in the winter–spring period of 2019, studies of the composition of OCs in the water of the Bureya Reservoir were carried out both before and after blasting operations. Spectral and chromatographic methods for determining OC have shown their influence on CHB number. Thus, upstream of the landslide body, the total OC_{254} content differed slightly off the coasts, which was reflected in the comparable CHB number (Table 1). However, downstream of the landslide body, there was a change in the quantitative and qualitative composition of OCs due to water infiltration, which affected CHB number. Moreover, on the left bank, where the landslide occurred, the CHB number was 2.3 times lower than on the right bank, where the forest was destroyed as a result of the tsunami. This could be due to the different composition and quantitative ratio of plant organic matter supplied with the surface runoff. After blasting operations, a pronounced increase in the total content of OC_{254}, aromatic compounds OC_{275}, and a change in the qualitative composition of volatile OC were observed in water samples collected from an artificial channel in February 2019. Suspended matter in the channel was an important factor in water quality. In water samples with a finely dispersed suspension, the maximum number of CHB was detected. It can be assumed that the increase in CHB was due to soil microorganisms and bacteria developing in the pore space of rocks, which entered the water during their grinding. This is confirmed by a significant change in water quality in March 2019. As a result of the leaching regime of the loose slopes of the channel, the total content of OCs and the CHB number decreased to values comparable to their content in the reservoir above the landslide.

Activity of microbial communities in vitro on easily available substrates. Experimental studies showed that planktonic bacteria present in the water around the landslide body utilizing lactate (a product of plant residue transformation) did not differ significantly in their activity (Fig. 3). However, in water samples collected from the flow channel, the activity of microorganisms changed over time: from the minimum values immediately after blasting to a subsequent increase of more than 2 times in March 2019. The maximum activity on nitrogen-containing substrate (peptone) utilization was observed in MCs from water samples collected in the channel at high flow rates, despite a low number of microorganisms. The results indicated that no direct relationship was revealed between the number of microorganisms and activity of the MC.

It is possible that, immediately after the blasting operations, physiological groups with low activity in relation to lactate dominated in the water of the channel, or some volatile organic substances had a toxic effect on them.

MCs present in water samples collected above and below the landslide body differed insignificantly by growth activity on easily available OCs (peptone and lactate). The community of microorganisms from the

Table 1. Content of organic compounds and number of cultivated heterotrophic bacteria in the water of the Bureya Reservoir in the landslide area

Site and date of sampling	OC_{254}	OC_{275}	Volatile OC	CHB number, CFU/mL
Before blasting operations January 25, 2019				
Above the landslide:				
left bank	0.324	0.282	Acetaldehyde, acetone, methanol, benzene, toluene	111.0 ± 9.6
right bank	0.303	0.196	Acetaldehyde, acetone, methanol, toluene, m-xylene, isopropylbenzene	101.3 ± 3.5
Below the landslide:				
left bank	0.524	0.312	Acetone, methanol, benzene, toluene, butyl acetate, ethylbenzene, *o*-, *m*-, *p*-xylenes, isopropylbenzene	63.0 ± 2.2
right bank	0.587	0.324	Hexane, acetone, methanol, benzene, toluene, butyl acetate, *o*-, *m*-xylenes, butanol, isopropyl benzene	144.7 ± 10.4
After blasting operations (chanel)				
February 14, 2019*	0.682	0.494	Acetaldehyde, acetone, methanol, toluene, *o*-xylene, isopropyl benzene	315.3 ± 3.5
	0.521	0.321	Acetaldehyde, acetone, toluene, *o*-, *m*-xylenes	173.0 ± 8.3
	0.753	0.545	Hexane, acetaldehyde, acetone, ethyl acetate, methanol, toluene, *o*-, *m*-xylenes, isopropylbenzene	484.7 ± 12.0
	0.724	0.514	Hexane, acetaldehyde, acetone, methanol, toluene, *m*-xylene, isopropylbenzene	414.7 ± 3.7
March 1, 2019	0.385	0.211	Hexane, acetaldehyde, acetone, ethyl acetate, methanol, toluene, *o*-xylene, isopropylbenzene	133.0 ± 12.8

* Water samples were collected from the right calm bank with an interval of 5 min; OC_{254} and OC_{275} are presented in conventional units of absorption.

artificial channel was less active immediately after the completion of blasting operations (February 14, 2019), probably due to the inhibition of the microbial community by detonation products present in the water. The activity of peptone and lactate utilization significantly increased in the MCs in the water samples collected from the channel in March. This may be due to the diffusion of OCs from the pore space of the landslide body after the crushing of rocks as a result of blasting operations.

During the spring snowmelt, the activity of MCs from water of the Bureya Reservoir was influenced not only by organic and mineral substances supplied after the landslide, but also by OCs entering with surface runoff from the catchment area. Experimental studies of the activity of MCs present in water, water extracts of rocks with fumes, and soils sampled on the landslide body have been carried out. Figure 4 shows MC activity on easily available carbon sources (peptone, yeast extract, lactate, and starch). Bacterioplankton showed minimal activity on all substrates used. Microorganisms present in the aqueous extract of the soil showed the maximum activity in relation to lactate and starch. The community from the water extract of the rocks destroyed by explosions occupied an intermediate position in this activity. This may be mainly due to the adaptation of soil microorganisms to the transformation products of plant residues. The growth activity of experimental MCs on lactate differed significantly and could depend on the combination of different cosubstrates. It is possible that the low activity of MCs from water samples was due to the presence of a wide range of growth inhibitors, including products of wood decomposition and the detonation of explosives.

It is known that, during the decomposition of lignocellulose, toxic cosubstrates can be formed in addition to lactate (Guo et al., 2010). For example, possible inhibitory effects after the entry of plant residues into the aquatic environment are associated with the products of lignocellulose transformation (furfural, coumaric, formic, and acetic acids). It has been experimentally shown that, depending on the methods of lignocellulose hydrolysis, the resulting furfural is a key inhibitor of microbial enzymatic activity, including those producing lactate derivatives (Van der Pol et al., 2014).

Transformation of humic substances in vitro. Icing with various colors was recorded in the landslide area. The chemical composition of icing is formed under the influence of cryochemical and biochemical processes. This makes it possible to assess the composition of pore water in soils/rocks and groundwater. The

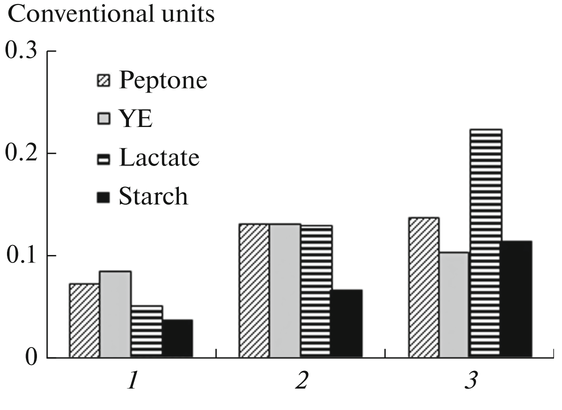

Fig. 4. MC activity of water (*1*), water extract of rocks with fumes (*2*), and water extract of soil from landslide body (*3*) in relation to different substrates.

icing may contain saturated and unsaturated hydrocarbons, methane, carbon oxides, ammonia, and hydrogen sulfide (Ivanov, 1998). The maximum CHB number (275 CFU/mL) was recorded in brown icing; it was 150 CFU/mL in transparent icing. It was assumed that, in icing, MC may participate in the transformation of humic organic matter present in soils and the pore space of rocks.

Humic substances are considered an integral component of organic matter in natural ecosystems which involved in many vital functions. They account for up to 70% of soil organic matter, 50–80% of dissolved OCs in surface waters, and 25% of dissolved OCs in groundwater. The composition of humic substances is formed as a result of the interaction of soils with surface and ground waters and largely depends on climatic conditions (Lipczynska-Kochany, 2018). Humic substances are considered supramolecular structures or associations of heterogeneous macromolecules, the genesis of which is associated with the degradation and decomposition of biological material (mainly plant residues) (Piccolo, 2001). The reactivity of humic substances in the environment depends on the set of functional groups (Bell et al., 2014; Lee et al., 2015), the size and shape of macromolecular structures, and the origin of organic residues (Rupiasih and Vidyanagar, 2005). Humic substances play an important role in biochemical processes. The complex macromolecular structure of humic substances determines their physicochemical characteristics and leads to unique and diverse interactions with different compounds and elements (Perminova et al., 2019).

Table 2. MC activity in relation to humus-containing substrate before and after blasting operations at the Bureya Reservoir

Sampling site	A_{254}/A_{436}	A_{465}/A_{665}
Before blasting operations		
Control (without inoculation)	3.42	3.79
Above the landslide, left bank	3.75	3.60
Below the landslide		
right bank	3.70	3.42
left bank	3.51	3.58
After blasting operations		
Control (without inoculation)	3.27	3.69
Sample of water from channel (March, 2019)	4.66	4.18
Extracts of rocks with fumes	4.57	3.97
Extracts of soil from landslide surface	4.47	4.02

A_{254}/A_{436} adsorption coefficient reflecting amount of the chromophore in HNa molecule;
A_{465}/A_{665} ratio between aromatic and aliphatic groups in HNa.

The color of a solution of humic substances is determined by the presence of chromophore functional groups: nitrogen-containing (–N=N–), azomethine (>C=N–), carboimine (>C=NH), nitro- ($-NO_2$), and nitroso groups (–NO). An increase in the intensity of coloration of the aquatic solutions occurs due to the presence of ketone and auxochromic groups in the aromatic rings (Chen et al., 2002).

To determine the activity of MCs during the transformation of the humus-containing substrate, various coefficients were calculated based on the change in the ratio of the spectral characteristics of the culture fluid after 30 days of cultivation (Table 2). Water samples collected around the landslide from the artificial channel and 5-day water extracts of soil and crushed rocks collected on the landslide body next to the channel were used as an inoculum (1 mL : 10 mL of M9 medium). A solution of the preparation without inoculum was used as a control.

According to the results, planktonic MCs in the water around the landslide body were less active with respect to the humus-containing substrate. In comparison with the control, the amount of chromophore groups and aromatic compounds in the culture fluid changed insignificantly. However, after the blasting operations, the transformation of HNa was more active with the participation of the MC from water sampled from the channel and the MC from aqueous extracts of natural substrates. During the experiment, the coefficient reflecting the number of chromophore groups (A_{254}/A_{436}) increased significantly, while A_{465}/A_{665} reflecting the ratio between the content of aromatic and aliphatic groups decreased. MC from an aqueous extract of crushed rocks was the most active with respect to the aromatic component of the humus-containing substrate. This may be due to the presence of decomposers of aromatic compounds in the pore space of rocks and their activation within 5 days in an aqueous extract.

Experimental studies have shown that, after blasting operations and an increase in the degree of rock dispersion, the activity of microorganisms capable of

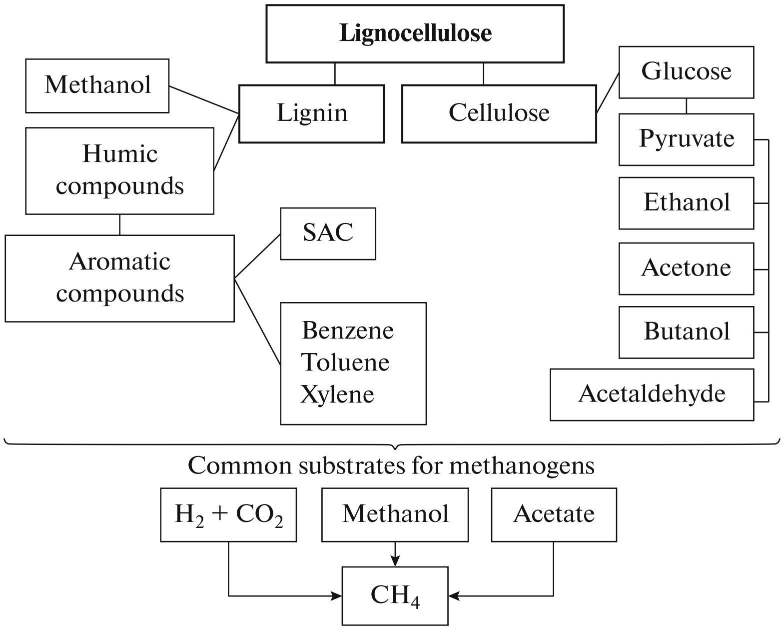

Fig. 5. Lignocellulose transformation and methane production.

destroying aromatic compounds increased. In fact, when water interacts with rocks, the concentration of volatile OC increases, which was confirmed by their presence both in the gas phase above the rocks and in the water extract (acetone, butanol, butyl acetate, hexane, methanol, ethyl acetate, toluene, and *m*- and *o*-xylenes). Methylated benzene derivatives (toluene and xylenes) found in the water around the landslide and in water extracts of rocks and charred wood are dangerous for aquatic organisms and can cause prolonged temporal and spatial risks (Kondratyeva et al., 2020). When exposed to microorganisms-destructors, many methylated benzene derivatives can undergo transformation and destruction, significantly changing the quality of water (Gopinath and Dhanasekar, 2012).

Genesis of volatile organic compounds. The spectrum of OC in water samples and water extracts detected in the present study made it possible to hypothesize that many of these compounds are of natural origin and are closely related to the microbial decomposition of plant residues and the methane cycle (Fig. 5).

First, important precursors of volatile OC found in water samples from the Bureya Reservoir may be decomposition products of plant residues (flooded wood): water-soluble compounds (sugars, organic acids, and alcohols), poorly soluble substances (hemicellulose), insoluble substances (starch, pectin, cellulose, waxes, fats, resins, and hydrocarbons), and hardly degradable lignin. Under aerobic conditions, they are oxidized during the respiration of microorganisms to carbon dioxide and water, while under anaerobic conditions they are fermented to form organic acids (acetic, succinic, butyric, lactic, and formic), alcohols (ethanol, butanol, and propanol), acetone, and gases (carbon dioxide and hydrogen). Fungi of the genera *Trichoderma*, *Fusarium*, *Myrothecium*, and *Penicillium*; myxobacteria of the genera *Archangium* and *Polyangium*; cytophages of the genera *Cytophaga* and *Sporocytophaga*; and bacteria of the genera *Vibrio*, *Achromobacter*, *Pseudomonas*, and *Bacillus*, as well as actinomycetes, of which the most active are representatives of the genera *Streptomyces*, *Micromonospora*, and *Streptosporangium*, are involved in aerobic processes. Bacteria of the genus *Clostridium* are actively involved in the anaerobic decomposition of plant residues.

Second, many alkanes (methane, ethane, propane, and hexane) are present in sedimentary rocks, oil fields, coal seams, bog waters (Godwin et al., 2013; Meslé et al., 2013), and reservoir sediments (Dzyuban, 2016). Due to their enzymatic oxidation/hydrolysis, various metabolites are formed, including acetone, butanol, etc. The genesis of methanol present in many samples may be associated with the transformation of natural methane by representatives of the Methylococcaceae and Methylophilaceae families (Yu et al., 2017).

Biogenic methane in turn is a product of aerobic and anaerobic methanogenesis. Microorganisms use a mixture of H_2 + CO_2, acetate, methanol, methylamines, methylthiols, and complex aromatic compounds as the main substrates for methane synthesis. (Liu and Whitman, 2008). Methanogens are phylogenetically diverse. They differ in the biochemistry of catabolic pathways and carry out different types of methanogenesis including hydrogenotrophic, acetoclastic, classical methylotrophic and methyl-reducing (Meslé et al., 2013; Callistova et al., 2017).

Taking into account the above, it can be assumed that the presence of gaseous components (CH_4, CO_2, H_2) in the pore space of rocks could become a reason for their explosive release during a sharp change in temperature and a landslide from the left bank of the Bureya Reservoir. Subsequently, they were included in biogeochemical processes, which led to the formation of a number of volatile OCs detected in the water around the landslide body. After blasting operations, hexane, acetaldehyde, acetone, methanol, toluene, xylenes, and isopropylbenzene occupied a dominant position. Some of these components could be the detonation or decomposition products of trinitrotoluene and hexogen.

At this stage of research, it is difficult to determine in which case some of the volatile OMs were the transformation products of plant residues or metabolites that formed as a result of the functioning of methanotrophs/methylotrophs and explosives destructors (TNT and RDX). All these products are components of complex processes of the transformation and biogenesis of organic substances.

CONCLUSIONS

Microbiological studies at the Bureya Reservoir after a giant landslide during the freeze-up period established a significant change in the quality of water below the landslide body due to its drainage through destroyed rocks. The most significant changes in the number and activity of MCs were detected under the influence of the detonation products of TNT and RDX and their microbial metabolites after blasting operations.

In the artificial channel, an increase in the total content of OCs and aromatic compounds was accompanied by an increase in the number of cultivated heterotrophic bacteria. MCs formed in water extracts of soil and rocks crushed by explosions had potential activity with respect to easily available organic substrates and humic compounds. Many of the identified volatile OC are formed as a result of the vital activity of methanogenic and methanotrophic bacteria, including methanol and methylated benzene derivatives.

After the collapse of the landslide and restoration work, a wide range of aromatic compounds of natural and anthropogenic origin was detected in the water of the reservoir, which can affect the number of destructive bacteria, reduce the self-remediation potential, and deteriorate water quality. Wood residues on the banks of the reservoir after a landslide and tsunami will undergo microbial transformation for a long time and increase the color of water due to its humification and an increase in the concentration of high-molecular OCs, including toxic polycyclic aromatic hydrocarbons.

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COMPLIANCE WITH ETHICAL STANDARDS

The authors declare that they have no conflict of interest. This article does not contain any studies involving animals or human participants performed by any of the authors.

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