December 11, 2018 Landslide and 90-m Icy Tsunami in the Bureya Water Reservoir

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Abstract

On December 11, 2018, a large (with an estimated volume up to 25 million cubic meters) landslide occurred in the middle part of the Bureya water reservoir (Russian Far East). The landslide has completely blocked the river bed and prevented the replenishment of the Bureya HPP reservoir from a large part of its catchment area. In the deep (down to 70 m) reservoir, the landslide generated a destructive tsunami-like wave whose impact on the shore was emphasized by a thick (up to 20 cm) ice cover. The maximum run-up that was reached at the point 2.8 km away from the landslide on the right bank of the Sredniy Sandar river which flows into the reservoir just against the landslide, turned out to be equal to 90 m. The maximum penetration of the wave along the Srendiy Sandar valley was 3.75 km, the water stopped at an altitude of 78 m above the initial water level leaving a pile of tree trunks up to 2 m in height. The maximum run-up reached on the gentle slope of the right (northern) bank, faced directly to the landslide, was up to 62 m, with an inundation distance up to 650 m from the water edge. All the trees and soil cover in this area were completely removed. The height of the mound of broken trees left at the inundation limit in this area reached 5 m. The run-ups on the left (southern) slopes, at a distance of up to one kilometer from the landslide, were within 35–45 m in upstream direction, and within 25–35 m in the downstream direction. Field surveys found that the actual run-ups were by 5–10 (sometimes up to 15) meters higher than the trim line of complete forest and soil destruction visible in air photos and satellite images of the affected area.

Keywords

Tsunami • Landslide • Run-up • Inundation • HPP water reservoir • Tsunami hazard

Introduction

On December 11, 2018, at 14:48 of local time, a large (with an estimated volume up to 25 million cubic meters) landslide occurred on the left (southern) slope of the Bureya water reservoir (Russian Far East) (Fig. 1). The landslide occurred in the middle part of the reservoir where the river valley is oriented almost strictly from east to west. The Bureya river is the third-longest (after the Zeya and the Usury rivers) tributary of the Amur river, the largest river in the Russian Far East. The Bureya HPP built in 2009 with its dam of 140 m high and 20.9 km^3 water reservoir plays an important role in the Russian Far East electric supply system. It has installed capacity of 2.1 MW and produces up to 17% of electricity in the regional electric system. The landslide completely blocked the river bed and prevented the replenishment of the Bureya reservoir from a large part of its catchment area that created a federal-level emergency situation. In the deep (down to 70 m) water reservoir, the landslide generated a destructive tsunami-like wave whose impact on the banks was emphasized by a thick (up to 20 cm) ice cover.

The climate of the area is sharply continental, with the long cold winter (average January temperature is about −28 °C) and relatively short warm summer (average July temperature is about +18 °C). Vegetation is dominated by forests consisting mostly of larch-trees and birch-trees with minor inclusions of pine-trees and alders. One of important features of the territory is the wide presence of permafrost

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Fig. 1 General view of the landslide scar on the southern slope of the left bank and the landslide body blocking the river bed. Note the trees, remaining in inclined but standing position on the top of the rear part of the landslide. Photo by A. Makhinov taken on 25.12.2018 from a helicopter MI-8

rocks with thickness from 50 to 100 m (Kondratieva 2019). The islands of permafrost are associated with the river valleys and the northern slopes of the terrain.

The landslide did not have any discernible trigger. It occurred in winter in very stable weather conditions when the average daily temperatures were about −30 °C. Despite the Byreya reservoir is located in the earthquake-prone region, no seismic quakes were recorded in this particular area for that day.

Due to the remoteness of the area and the fact that the region is sparsely populated, the event went unnoticed and become publicly known only on December 22, 2018 when two local hunters came to the site and took photos of the affected area. The first reconnaissance helicopter flight to the site was made on December 25, 2018. This quick survey, however, confirmed that the landslide had completely blocked the river bed and generated a destructive tsunami-like wave that removed the forest and the soil in the area of most severe impact (Fig. 2). The first on-site field survey was completed in the middle of January 2019, when the initial instrumental measurements of the landslide body were made. This was followed by several other short-time helicopter visits made in February, March and April 2019, but a detailed on-site survey of the landslide and tsunami run-up measurements were only performed in June 2019.

In mid-February 2019, the Russian Ministry of Defense carried out a special operation to make a water passage in the body of the landslide and restore the integrity of the basin to provide a free flow from the upper to the lower part of the reservoir. This was done to ensure the normal functioning of the Bureya HPP and to prevent flooding of the settlements and roads upstream the landslide during spring flood. The initial 50 m wide passage made in February was widened up to 150 m in April-May by spring waters flow that eventually eliminated the risk of flooding.

For the Russian territory, the occurrence of such a significant tsunami-like phenomenon generated by a coastal slope failure, is a rare event but on a global scale such phenomena occur quite regularly. Only for the last two decades, the global tsunami catalog has recorded five large (more than 50 m in height) landslide-generated tsunamis that occurred on the banks of reservoirs, lakes, fjords and bays: November 21, 2000 Greenland (51 m); April 21, 2007 Aysen Fjord, Chile (60 m); April 4, 2007 Chehalis Lake, Canada (38 m); October 18, 2015 Icy Bay, Alaska (190 m); June 17, 2017 Greenland (90 m). Historically, a record-high

Fig. 2 The area on the right (northern) bank of the Bureya reservoir near the mouth of the Sredniy Sandar river. Note the evident trim line, below which vegetation and soil cover have been completely removed by the upslope water flow and the gullies produced on the steep coastal slope by backwash curents. Photo by A. Makhinov taken on 25.12.2018 from a helicopter MI-8

(525 m) wave was generated on July 10, 1958 in Lituya Bay in Alaska after a collapse of its steep eastern slope, triggered by a strong local earthquake (Miller 1960). The largest hydraulic disaster caused by a slope failure occurred on October 9, 1963 on the Vajont Dam in northern Italy. A collapse of 270 million cubic meters of rocks from the steep slope of Monte Toc located in the immediate proximity to the dam, caused a 250 m wave that overtopped the dam and rushed down a narrow gorge, destroying the downstream villages of Langarone, Piave and Rivalta where 1910 people were killed (Panizzo et al. 2005).

Landslide

The landslide occurred in the middle part of the Bureya reservoir about 90 km from the dam, at the point of 50.5589° N, 131.4719° E. In this area, the Bureya river flows almost strictly from east to west; its valley forms a deep gorge with a high (about 400 m) and steep (slopes up to 30–35°) left bank and a relatively flat, terrace-like right bank of about 1 km wide that goes up to 50 m above the present water level. After construction of the dam, the valley was flooded to form a water reservoir of about 500–550 m wide and down to 70 m in depth. The tributaries' estuarine sections are also filled with water and form narrow and deep bays of 1–3 km long. In this part of the river channel, the water flow is pressed to the left bank and cuts the base of the slope, constantly increasing the steepness and reducing its stability.

The bedrocks composing the steep left slope of the valley are represented by Proterozoic igneous rocks penetrated by younger dikes (Makhinov et al. 2019). In this area, the rocks are severely fractured by inclusions of stronger monolithic blocks up to several meters in size. The fracturing essentially weakened the stability of the slopes, preparing the conditions for a massive slope failure. After the beginning of reservoir filling, groundwater began to penetrate under the base of the slope, increasing the water content in the fractured rock in its lower part and reducing slope stability. The stability is further reduced due to significant (15–20 m in range) fluctuations in the water level caused by seasonal variations of the flow rate and uneven HPP water consumption that led to accelerated erosion of the lower part of the slopes.

The failure of the southern slope occurred at the elevation of ~550 m above the initial water level at the time of the event. The landslide's separation bowl is deeply cut into the slope and, being rectangular in plan, has a considerable size of about 600 m in length and 500 m in width (Fig. 3). Along the upper edge of the amphitheater there are several small blocks of rocks that are marked by gaping cracks and ready for displacement but remain in place. In the lower part of the amphitheater formed a thin cover of rock fragments of different sizes that continuously roll down from the exposed slope.

Fig. 3 General view of the landslide scar on the southern bank of the Bureya water reservoir and the body of the landslide with a passage, initially made in February 2019 and then extended by the spring flood in April-May 2019. Photo by A. Ostroukhov taken from quadrocopter "Fantom4" on June 19, 2019

The landslide completely blocked the reservoir with a high rocky dam of 800 m in length and from 150 m (at its base) up to 620 m (in the middle part) in width. The total surface area of the landslide body is 270 thousand m^2. The landslide's total volume calculated based on the results of geodetic measurements, is 24.5 million m^3, with about 4.5 million m^3 of rocks in its surface part. In plan, the landslide body has a fan-shaped form and a complex relief (Fig. 4). The main body of the landslide is shifted to the right bank, which indicates that the slide was of high speed and significant kinetic energy. The wide rear part of the landslide is represented by weakly deformed strata of displaced bedrock, as well as by chaotic piles of huge monolithic blocks and smaller debris. The frontal part of the landslide, which was stopped by the ledge of the terrace-shaped slope of the right bank, underwent the most significant deformation. As a result, several short and high mounds were formed in its upper part, separated by rather deep linear depressions in the form of steep slope ditches (Makhinov 2019).

The rock mass entered the water reservoir and produced a destructive tsunami-like wave that traveled upstream and downstream at a distance exceeding 10 km. The water wave stripped vegetation up to tens of meters above the shoreline and eroded soil layer down to the depth of freezing (70 cm) along extended parts of the shore.

A prominent trim line is evident in these areas, below which vegetation has been almost completely removed. Along the shoreline, the geomorphic impacts of tsunami differ over short distances due to changes in shoreline configuration and slope steepness. The erosion is most severe near the landslide, especially in the areas of the north coast that lie directly against the collapsed slope. Erosion traces are less noticeable further from the landslide and on the bank slopes, protected from direct exposure to waves. The degree of erosion also decreases upslope, away from the shoreline where the soil cover remains largely undamaged due to reduced velocity of currents.

Tsunami Impact

Due to severe winter conditions in the area (thick snow cover, low daytime temperatures), the detailed instrumental measurements of the run-up heights are possible only in the

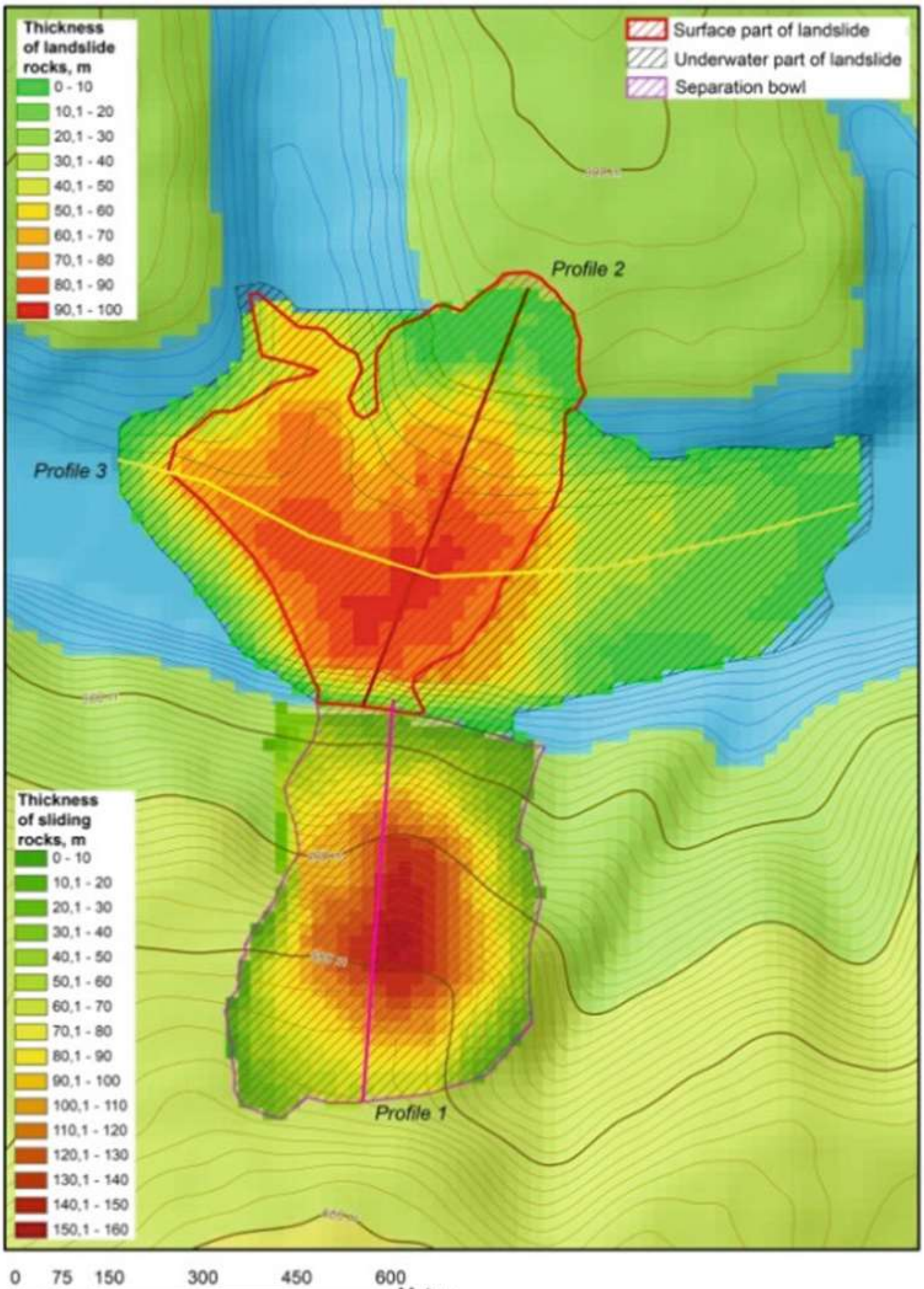

Fig. 4 Model of the landslide based on the results of field geodetic measurements made in January of 2018

summer season after the ice cover melts and the annual spring flash flood passes. These measurements were made during a field survey of the affected area that was conducted in the second half of June 2019.

During the field survey, the inundation boundaries and tsunami run-up heights were substantially clarified as compared to their initial estimates obtained from the analysis of air photos and satellite images. In total, about 50 run-up heights were measured using a barometric altimeter built into the Garmin portable GPS receivers. Before each measurement or a series of measurements at nearby points, the receiver was zeroed to the reservoir's water level on the day of measurement. The absolute water level in the landslide area was obtained by interpolating the elevation marks at the hydrological posts of the Bureya HPP dam and in the Chekunda village that have a long continuous history of level monitoring.

In June 2019, six months after the event, the limit of the wave run-up along the slopes was clearly marked by the presence of tree branches and pieces of wood on the upslope side of tree trunks, which were flooded but remained intact. The in-site measurements demonstrated that the actual run-ups were by 5–10 (sometimes up to 15) meters higher than the trim line visible in air photos and satellite images made soon after the event. Near the upper limit of inundation, partially uprooted tree trunks indicated the water flow direction that had generally gone up the slope away from the reservoir, but in some cases—toward the reservoir (due to backwash).

Along the large part of the trim line clearly visible on air photos and satellite images, the wave left the piles of broken and damaged trees (Fig. 5). Backwash currents produced deep (up to 1.0–1.5 m) gullies on the steep parts of the right (north) bank lying directly against the landslide (Fig. 6).

The most severe impact of the water wave fell on the banks of the Sredniy Sandar river that flows in the Bureya river just across the landslide (Fig. 7). The highest wave run-up, 90 m above the initial water level at the time of the event, occurred at the right bank of Sredniy Sandar river, 2.8 km away from the landslide (Fig. 8). This value puts the Bureya tsunami of December 11, 2018, in the seventh place on the world list of the strongest tsunamis of landslide origin having instrumental measurements of this parameter. The maximum penetration of a water wave along the valley of the Sredniy Sandar was 3.75 km, its progress stopped at an altitude of 78 m above the initial water level at the point of 50.5844° N, 131.4629° E, where the wave left a pile of tree trunks up to 2 m in height. The backwash current from the Sredniy Sandar valley carried all the cut trees back in the Bureya reservoir to cover the water surface with an almost continuous layer of damaged tree trunks with stripped branches. This thick layer of wood remained frozen in ice until the end of May when the spring flood cleared the water surface from floating trees.

The gentle coastal slope on the right (northern) bank lying directly opposite the landslide suffered the strongest wave impact. The high velocity water flow completely removed both vegetation and soil leaving only damaged stumps and exposed tree roots on the place of dense forest that grew here earlier (Fig. 9) The maximum inundation level reached here 62 m with maximum horizontal flooding up to 650 m.

The run-up heights on the left (southern) slopes of the reservoir, located within a distance of up to 1 km from the landslide, were within a range of 36–48 m in the upstream direction and 25–33 m in the downstream direction. At the same time, the run-up decreased (down to 15–20 m) at the parts of the left coast directly adjacent to the landslide. On several sharp breaks of the reservoir's coastline (capes) the wave had overlapped the capes and the water stream had rolled into the neighboring bays.

Fig. 5 Debris along the inundation limit formed by the cut and broken trees. Photo by V. Gusiakov

Fig. 6 Gullies on the opposite (right) bank of the Bureya river made by the backup wash currents. Photo by V.Gusiakov

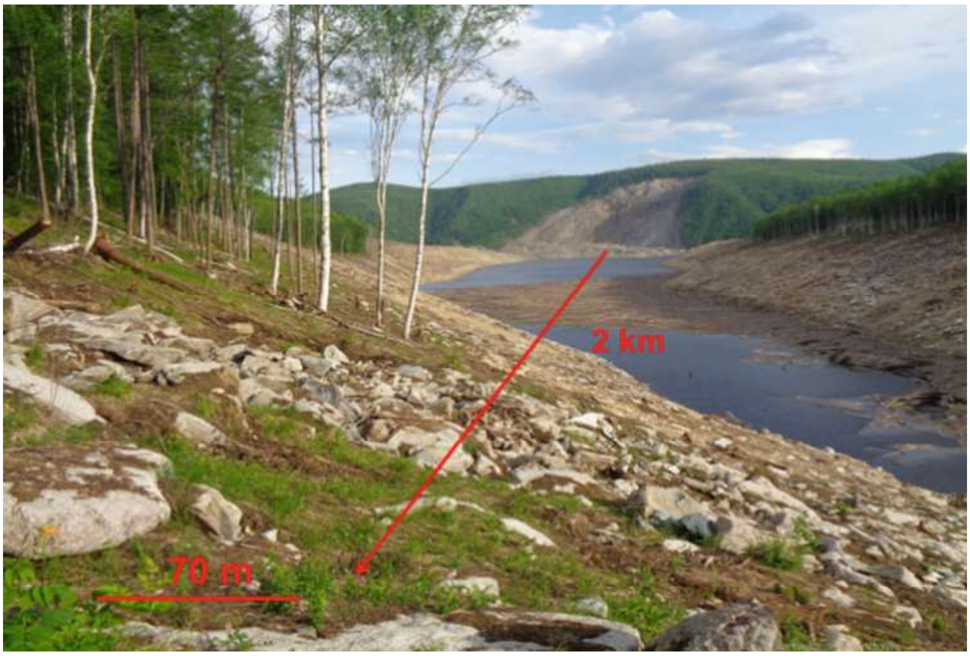

Fig. 7 Right bank of the Sredniy Sandar river. The inundation reached here 70 m above the initial water level at the distance about 2 km from the landslide. Photo by V. Gusiakov

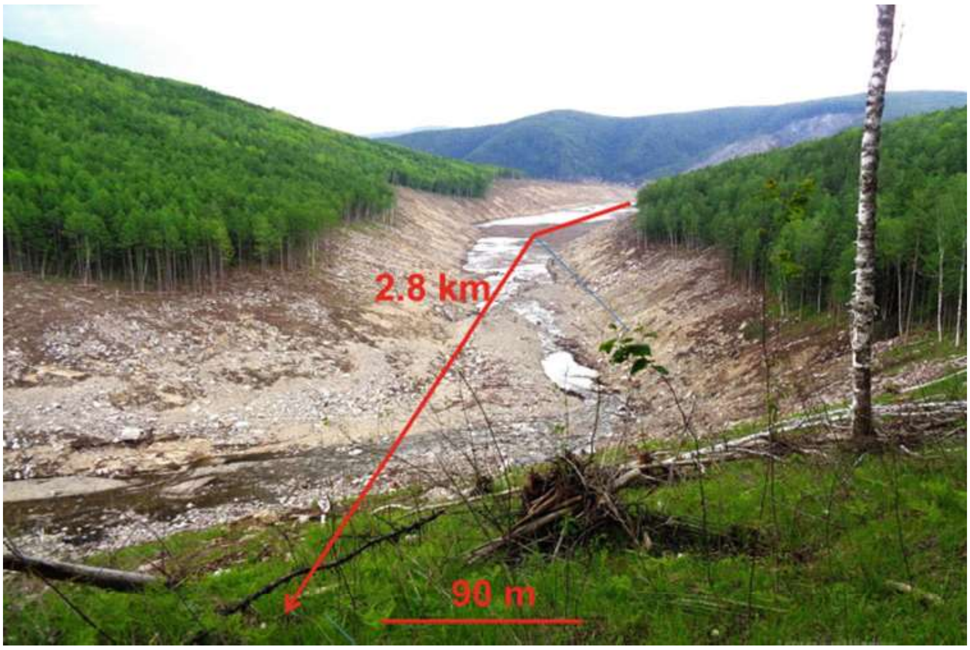

Fig. 8 Left bank of the Sredniy Sandar river. The place of the maximum run-up height (90 m above the initial water level) reached here at the distance about 2.8 km from the landslide. Photo by V. Gusiakov

Fig. 9 Damaged stumps and exposed tree roots on the gentle coastal slope located directly opposite the landslide on the right (northern) bank of the Bureya River. Note the clearly marked trim line on the left (southern) bank of the reservoir. Photo by A. Makhinov taken on 25.12.2018

The overview map of all the measured run-ups of the Bureya tsunami plotted in the PDM/TSU graphic shell (PDM/TSU 2020) is shown in Fig. 10. In this map, run-ups are plotted as the scaled vertical lines positioned according to the geographical coordinates of run-up measurement point. The run-up distribution demonstrates a strong directivity of the water wave produced by slope failure with its energy maximum radiated in the direction of mass movement and the leading role of narrow river valleys in increasing the wave height.

Conclusion

The coastal landslide that occurred on the left bank of the Bureya water reservoir on December 11, 2018 is the largest event of this type that happened in the Russian Federation for the last decades. The landslide did not have any discernable trigger. It occurred in winter in very stable weather conditions with the average daily temperature of about −30 °C. No seismic activity was recorded in this area for that day. The

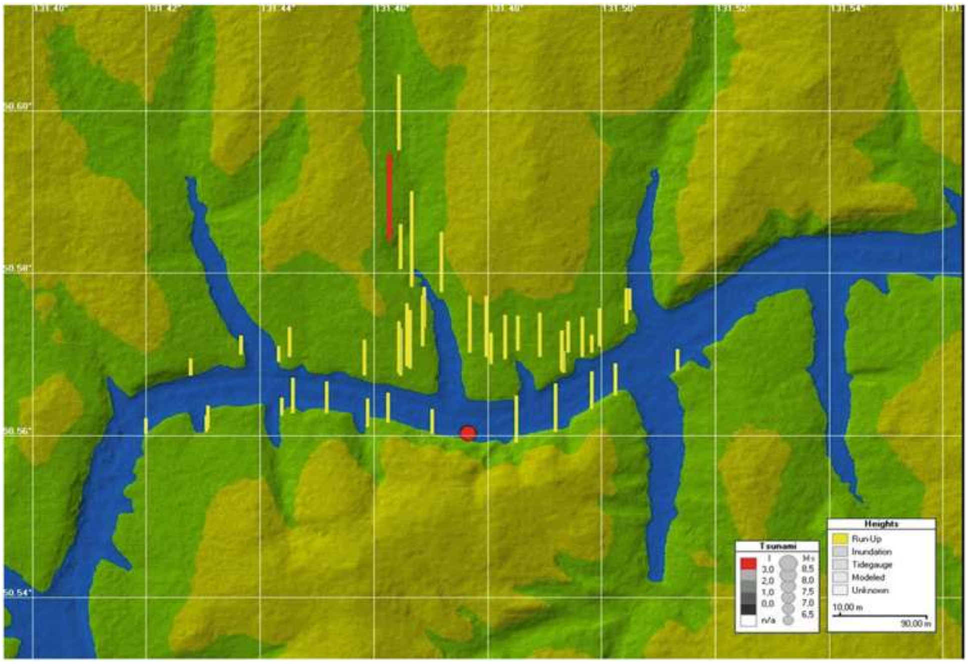

Fig. 10 Map of the measured run-up heights of the Bureya tsunami plotted in the PDM/TSU graphic shell. The red dot marks the landslide. The highest run-up (90 m) is highlighted in red

landslide completely blocked the Bureya River bed and prevented water supply from the 2/3 of river's catchment area that was critical for the normal functioning of the Bureya HPP in winter conditions when the water supply is low.

The event occurred in the very remote, sparsely populated area of the Russian Far East and remained unnoticed for more than a week. The first reconnaissance helicopter flight to the site was made only on December 25, 2018. Due to severe winter conditions in the area (thick snow cover, daytime temperatures down to −35 °C), the detailed field survey was conducted only in June 2019 after the annual spring flash flood was over. During the survey, the detailed instrumental measurements of the landslide body and tsunami run-up heights along the river banks were made.

The landslide generated a destructive tsunami-like wave whose impact on the banks was emphasized by a thick (up to 20 cm) ice cover. The maximum run-up at the right bank of the Sredniy Sandar River reached 90 m above the initial water level at the time of the event. The maximum penetration of the water wave along the valley of the Srendiy Sandar River was 3.75 km, the water stopped at the altitude of 78 m above the initial water level.

In the area of large run-up, high-velocity water currents loaded with thick ice cut or uprooted all the trees (mostly larches and birches) and completely removed the soil down to freezing depth (about 70 cm). Backwash currents produced deep (up to 1.0–1.5 m) gullies on the steep parts of the right (north) bank lying directly against the landslide.

In June of 2019, six months after the event, the upper limit of water inundation along both river banks could be still clearly identified by the tree remnants and the piles of tree trunks left by water along the line of maximum in-land penetration. In the field survey, it was found that the actual run-ups were by 5–10 m (sometimes up to 15 m) above the trim line identified on the air photos and satellite images.

The wave energy decay and run-up heights are determined by a distance to landslide, bathymetry and shoreline configuration relative to a wave propagation direction. The observed pattern of run-up heights suggests that the landslide mass and velocity drive the initial wave size, while the energy decay and inundation heights are defined by a combination of distance to the landslide, bathymetry, wave propagation direction and shoreline configuration.

Propagation of the water wave along the river bed both in upstream and downstream directions was limited by a distance of 10–12 km, although soon after the event the traces of water disturbance was clearly visible (as the lines of broken ice along the coastline) up to the distance of 20–25 km.

The Bureya landslide occurred far away (90 km) from the Bureya HPP and did not directly affect the station's dam. However, the event has demonstrated the potential threat of slope instability for the safety of HPP dams, especially for those having their water reservoirs in a mountain region. In Russia, the two largest HPPs (Sayano-Shushenskaya and Krasnoyarskaya HPPs) are located in such regions. Engineering surveys of slope stability within at least 10 km of HPP dams should be a high priority task to ensure the safety of both HPPs.

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