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SURFACE AND GROUND WATERS IN TERRESTRIAL PERMAFROST REGION

ASSESSMENT OF POSSIBLE CONSEQUENCES OF OUTBURST FLOODS: CASE STUDY OF THE BODOMDARA RIVER VALLEY (TAJIKISTAN)

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The prerequisites and modeling of possible outburst floods in the valley of the Bodomdara River (Tajikistan) are considered using detailed field data. According to the route survey results, Upper Bodomdara Lake is a supraglacial lake, which assumes possibility of its outburst leading to a cascade outburst flood. The depression of Lower Bodomdara Lake is relatively stable, and its outburst is possible without cascade flooding at anomalously high temperatures, upon snowmelt combined with extreme rainfall. Two probable scenarios are considered: (I) the outburst of Lower Bodomdara Lake (its volume comprised 328,000 m^3 according to the bathymetric survey of 2020) and (II) the cascade outburst flood of Upper Bodomdara Lake (700,000 m^3). Digital elevation model (DEM) ALOS PALSAR (12.5 m) and DEM based on images from an unmanned aerial vehicle for the Bodomdara River alluvial fan were used for predicting flood consequences. The outburst flood hydrographs for scenarios I and II were obtained using the lake outburst model developed by Yu.B. Vinogradov and an empirical formula, respectively. The material increment was estimated in the transport-shift model of debris flow formation. The resulting hydrograph was applied for zoning the Bodomdara and Shakhdara river valleys with a total length of 75 km based on the FLO-2D model. According to the modeling, the maximum water discharge at the top of the alluvial cone of the Bodomdara River will reach 143 m^3/s under scenario I and 348 m^3/s under scenario II.

Keywords: *outburst floods, debris flows, transport-shift model, FLO-2D model, model of lake outburst, Tajikistan.*

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INTRODUCTION

Climate change leads to the degradation of mountain glaciation in Central Asia [*Jansky et al., 2009; Mergili et al., 2011; Wang et al., 2013; Harrison et al., 2018*]. The retreat of glaciers in the Pamir Mountains is mainly associated with an increase in air temperature [*Glazyrin et al., 2018*]. There are 6730 glaciers on the Pamir territory with a total area of 7493 km^2 [*Kotlyakov et al., 2011*]. In the eastern Pamir, glaciers revealed a tendency to accelerate melting from the late 1970s to 2001; the area of glaciers decreased by 7.8% in 1978–1990 and by 11.6% in 1990–2001 [*Khromova et al., 2006, 2014*]. The retreat of glaciers leads to the formation of glacial lakes.

Identification of potentially outburst-prone lakes is carried out using remote sensing data and route surveys [*Kääb et al., 2005; Quincey et al., 2007*]. The inventory of lakes in the upper reaches of the Amu Darya River on the basis of satellite images showed the presence of 1642 lakes, including 652 glacial lakes; 73% of all lakes are located above 4000 m asl. A tendency for a shift in the area of active growth of glacial lakes from the southwestern Pamir to the central and northern Pamir was also noted [*Mergili et al., 2013*]. According to the analysis of satellite images in 2007, 172 glacial lakes existed in the basins of the Gunt and Shakhdara rivers in the southwestern Pamir [*Mergili, Schneider, 2011*]. Most of them are located at 4400–4700 m asl and have been formed or at least significantly increased in size since 1968. The retreat of almost all glaciers and the growth of glacial lakes are observed in the southwestern Pamir [*Mergili, Schneider, 2011*]. In 2018, more than 600 mountain lakes were discovered in the Gunt River basin using multispectral images; most of them had been formed in recent decades [*Kidyaeva et al., 2020*]. A catalog of mountain lakes of the Gunt River basin with indication of their areas and genetic type of lake depressions was created. A strong outburst flood followed by a debris flow in the Pamir occurred in 2002 in the valley of the Dasht River [*Mergili et al., 2011*]. It was caused by the outburst of a thermokarst lake through underground flow channels. The area of the lake before the outburst was estimated at 37,000 m^2; according to other estimate [*Dokukin et al., 2020*], it reached 44,600 m^2).

As glacial lakes are located, as a rule, in hard-to-reach areas without systematic observations, it is quite difficult to predict outbursts. One of the ways to assess the risks associated with the outbursts of glacial lakes is mathematical modeling. If a glacial lake is located in the upper reaches of a river with a significant slope of its course, and if there is a sufficient amount of coarse-grained material in the bottom of the valley and on the adjacent slopes, the outburst of the lake is accompanied by debris flows with enormous destructive force. The complexity of the formation and movement of debris flows necessitated the development of a large number of mathematical models [*Hutter et al., 1994; Jan, Shen, 1997; Mikhailov, 2011*]. In various publications, models based on the equation of motion of a viscous fluid are often used to calculate debris flows. Hydrodynamic models are based on the solution of the Navier–Stokes equations of motion of a viscous fluid in explicit form or in the depth-integrated hydraulic form – the Saint-Venant equations of motion. According to [*Mikhailov, Chernomorets, 2011*], the FLO-2D hydrodynamic model is one of the most common in scientific research [*Cesca, d'Agostino, 2008; Mergili et al., 2011; Petrakov et al., 2012; Wu et al., 2013*]. Also, many models use a single-phase approach (similar to the Voellmy avalanche method), for example, the RAMMS (Rapid Mass Movements) model. The hydraulic model proposed by Voellmy does not take into account shear deformations [*Voellmy, 1995*]. In our study, a transport-shift model of debris flow formation was used to estimate the increment of material in a debris flow source [*Vinogradov, 1980; Vinogradov, Vinogradova, 2010*].

The aim of this study was to assess potential flooding zones in the valleys of the Bodomdara and Shakhdara rivers based on detailed field data using a set of mathematical models.

RESEARCH AREA

The research area includes Upper and Lower Bodomdara lakes located in the valley of the Darmaidovan River (Fig. 1), a large left tributary of the Bodomdara River.

The Bodomdara River flows into the Shakhdara River 49.5 km above the confluence of the latter with the Gunt River near the city of Khorog, the administrative center of the Gorno-Badakhshan Autonomous Region, Tajikistan. The length of the Darmaidovan River is 12 km [*Surface..., 1967*], and its catchment area is 65.6 km^2. The Darmaidovan River basin is elongated; its length is about 14 km, and the maximum width (in the middle part) is up to 5.5 km. The length of the Bodomdara River from the source of its left component Lyadzhvardara River is 27 km; the basin area is 318 km^2. The area of open glaciers in the studied part of the valley (without the Lyadzhvardara River basin) as estimated for August 11, 2020 was 6.66 km^2, and the total area of water reservoirs was 0.2 km^2. The length of the Shakhdara River is 142 km, the basin area is 4180 km^2.

In the upper reaches of the Darmaidovan River, the valley is composed of hornblende and biotite-hornblende gneiss with marble interlayers of the Yamchin formation; in the middle reaches, rocks of the Garmchashmin formation consist of biotite, sillimanite, and kyanite gneisses and migmatites predominate; in the lower reaches, granite-biotite gneisses of the Ptups formation occur.

According to the leading exogenous relief-forming processes in the valley of the Darmaidovan River, the following characteristic areas are quite clearly distinguished: a glacial moraine complex in the upper reaches of the valley (glaciers and sources); a section of moraine deposits in the upper part of the trough valley; a section of a stepped riverbed in the middle and lower parts of the valley; an estuary step; and an estuary section with sediment accumulation (with a superposed debris cone).

The mouth of the Darmaidovan River is located in the center of a flattened widening of the Bodomdara River valley with a length of about 1.2 km and a width of 100–160 m; the bottom of the valley is completely filled with alluvial deposits. At 600 m downstream, the slopes of the Bodomdara valley become noticeably higher on a step of the debris cone formed by right tributary. Further downstream toward the debris cone near the confluence with the Shakhdara River, the riverbed has a steplike profile. The average slope of the Bodomdara River downstream the Darmaidovan River is about 0.03.

The averaged longitudinal profile of the Darmaidovan riverbed is close to the slope of the bottom of the trough valley. The Darmaidovan River flows along the base of the right slope of a deep V-, sometimes U-shaped valley, between moraine deposits on the left bank and talus cones on the right bank. The width of the torrential flow in summer is 6–8 m increasing to 8–12 m in the lower reaches; the flow depth is about several dozens of centimeters with a maximum of about 1 m. In narrow parts, the river flow occupies the full bottom of the valley (6–7 to 10–15 m in width). Channel deformations are limited; the river channel is slightly curvy or straight, with numerous rapids and waterfalls. The bends of the

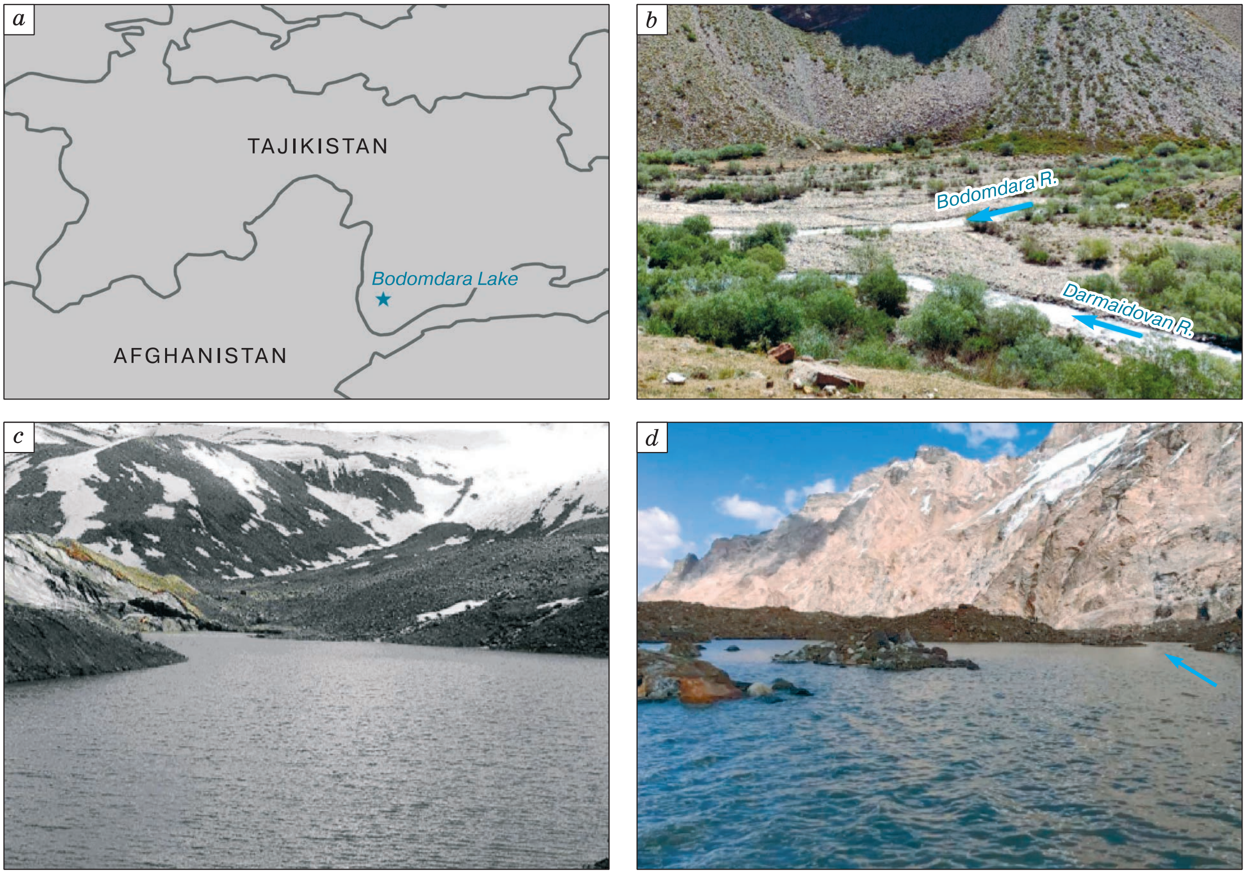

Fig. 1. Layout of the Bodomdara lakes:

(*a*) location of the Bodomdara lakes; (*b*) widening of the Bodomdara River valley at the junction with the Darmaidovan River (13.2 km upstream from the Bodomdara River mouth); (*c*) Upper Bodomdara Lake, a view of the southern part of the reservoir from the northwestern shore; (*d*) Lower Bodomdara Lake, a view of the lowering at the source of the lake (indicated by the blue arrow) from the southwest.

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channel are determined due to the impact of large debris cones in the mouths of tributaries or talus cones at the footslopes.

A specific characteristic of the Darmaidovan River as present is the absence of indications of debris flows. The slopes and bottom of the channel are overloaded with loose not rounded talus material; the vegetation cover with moss pillows in the middle reaches is traced directly to the water edge (Fig. 2), old-aged and low forest stands occupy widenings of

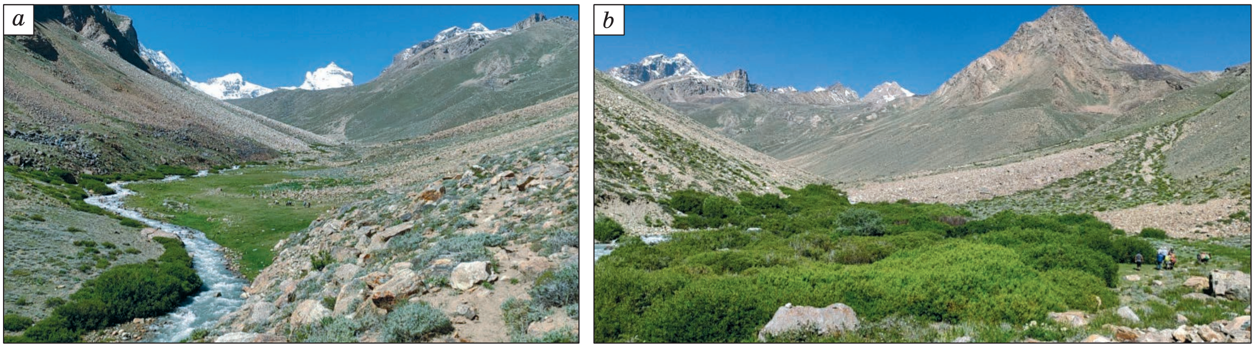

Fig. 2. Widenings of the bottom of the Darmaidovan River valley:

(*a*) 8 km upstream from the mouth, (*b*) 6.4 km upstream from the mouth; flattened area is completely overgrown with old stunted forest. In the distance, on the left slope, high moraine terraces and tributary valleys with rock bars in the lower reaches are seen.

the valley bottom in the lower reaches, and there are no characteristic debris flow-shaped landforms (U-shaped cuts, debris flow levee, terraces, etc.). There is no debris cone extended into the Bodomdara River valley in the mouth of the Darmaidovan River.

Glacial-moraine complex and lakes. A comparison of the positions the edges of active ice tongues on satellite images of 2008 and 2020 (Fig. 3) attests to their retreat by 50–120 m over 12 year; thus, the rate of retreat was up to 10 m/yr). The edge of the glacial-moraine complex is stable, but the ice wall above the river source has also retreated by 35–40 m (3 m/yr).

Lakes in the Darmaidovan River valley are located inside the glacial-moraine complex (Fig. 3), closer to the left side of the valley. These lakes are of different ages. Lower Bodomdara Lake appeared no later than in the last quarter of the 20th century; it is mentioned in the report of a tourist group that visited the valley in 1974. However, it is not mentioned in the description of the territory during a field survey of the Darmaidovan valley (up to the glacier) by P.N. Luknitsky performed on August 12, 1931 [*Luknitsky, 1955*].

According to the KH-9 satellite image from August 13, 1975 [*https://earthexplorer.usgs.gov*] the area of Lower Bodomdara Lake was 20,000 m^2, i.e., 2.6 times smaller than in 2020. According to the topographic map on a scale of 1:100 000 [*J-42-108 (Roshtkala), 1988*] fixing the situation for 1978–1984, the configuration of the lake resembled its modern configuration in that time.

Upper Bodomdara Lake appeared in the recent decade; it is absent on the satellite image obtained in August 2008, when only separate depressions with water existed in this area (Fig. 3). According to Landsat 7 image from August 20, 2010 [*https://earthexplorer.usgs.gov*], several large depressions that appeared in 2005 merged together, and the length of the lake reached 300 m. Since that time, the lake began rapidly increase in size; in 2020, its area was 56,100 m^2. Presumably, Upper Bodomdara Lake is the supraglacial lake, and glacier ice is still preserved under its bed. The lake is released from the ice cover for a short time at the end of July – the beginning of August and becomes covered with ice at the end of September.

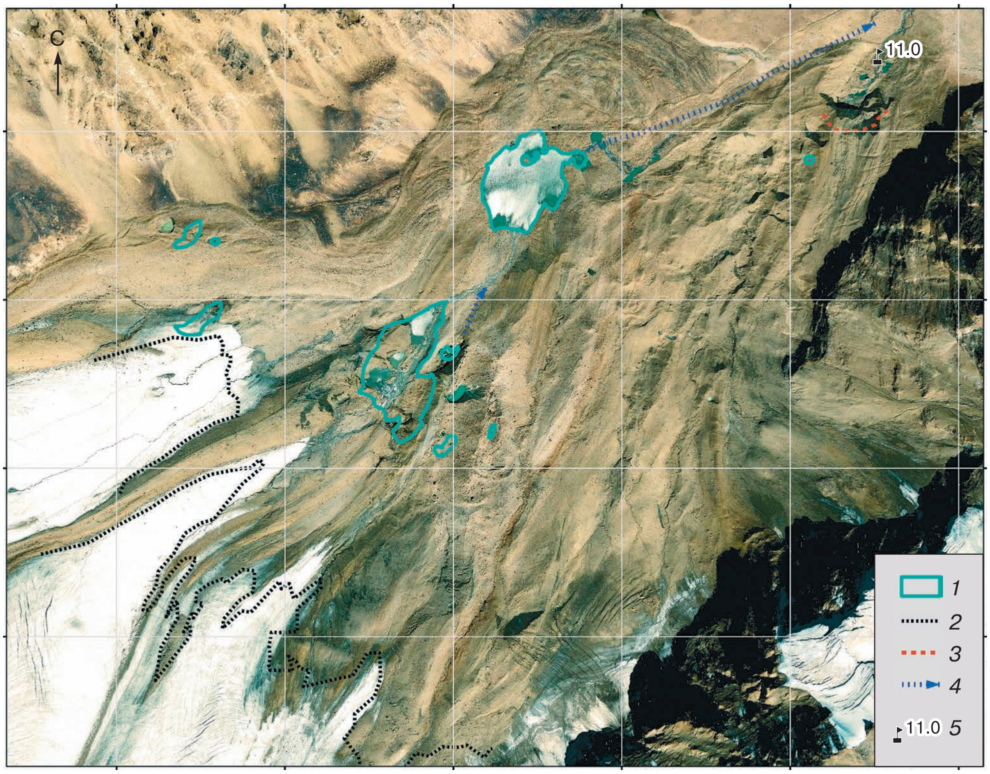

Fig. 3. The layout of lakes on the glacial-moraine complex in the upper valley of the Darmaidovan River (satellite image, August 2008).

(*1*) boundaries of lakes and ephemeral reservoirs on June 11, 2020; (*2*) edge of pure ice (active glaciers) on August 11, 2020; (*3*) edge of the ice wall at the source of the river on August 11, 2020; (*4*) the most likely ways of passing a possible outburst flood; and (*5*) distance from the mouth of the Darmaidovan River. The size of coordinate grid cell is 500 × 500 m.

Table 1. **Morphometric characteristics of the Bodomdara glacial lakes according to the bathymetric survey on July 30, 2020 (Lower Lake) and Sentinel-2B image for August 11, 2020 [*https://apps.sentinel-hub.com/eo-browser/*] (Upper Lake)**

Lake	Abs. height, m	Water area, m^2	Length along long axis, m	Max width, m	Average/max measured depth, m	Lake volume, million m^3
Lower	4289	54,000	300	235	6.2/21.8	0.328
Upper	4361	56,100	360	200	No data	No data

In 2020, both lakes had approximately the same water areas size (Table 1).

The supraglacial position of Upper Bodomdara Lake suggests further active deformation of its bed and shores as a result of melting/ retreat of the glacier. Further subsidence of its bottom and retreat and change in the outlines of its shores can be expected. The dam of the lake is unstable, which, in combination with the expansion of the lake, can lead to its outburst/water drain.

The bowl of Lower Bodomdara Lake is relatively stable. On the map of the 1988, the lake area is 40,900 m^2; at the end of the warm season in August 2008, the water area reached 49,200 m^2 (an increase by about 20%); in 2020 (after 12 years), its area increased to 52,000 m^2 (by of about 5%). Initially, the lake extended to the south and east due to active ice melting from the west side of the median moraine ridge. In the recent decade, its shoreline has been stable, and some increase in the area (taking into account the possible error) may be due to a decrease in the area of moraine islands in the lake. Currently, the lake is located in the depression made by the glacier. The depths in the center of the basin reach 22 m (Fig. 4).

The rectangular hydraulic network, along with the presence of lake-like expansion and the disappearance of surface flow into the loose material, indicates the presence of buried glacier cracks inside the dam of the lower lake. Further degradation of the dam body may lead to the isolation of individual blocks with an ice-frozen core inside and subsequent subsidence of the surface. A completely stable lake dam with a consolidated ice core and a frozen moraine cover may become unstable if current climate trends are preserved [*Harrison et al., 2018*]. An increase in the duration of the ablation period and higher summer temperatures will contribute to an increase in glacial runoff. An increase in the probability of extreme weather events (abnormal heat, sudden snowmelt, precipitation) against the background of increased runoff also poses the risk of an outburst of the lower lake.

Taking into account the unstable state of the Upper lake depression and the dam, a cascade outburst scenario – the outburst of the Upper lake as a trigger for the outburst of the lower lake – is also very likely. A possible outburst of Lower Bodomdara Lake will lead to a rapid erosion of its dam and the discharge of up to 200,000–400,000 m^3 of water. The formation of the erosional cut may follow the old flow path from the Lower lake (Fig. 4) with access to the current river cut 300–400 m downstream the current source. Loose material on the lower slope of the glacial-moraine complex is likely to be washed away to pure ice.

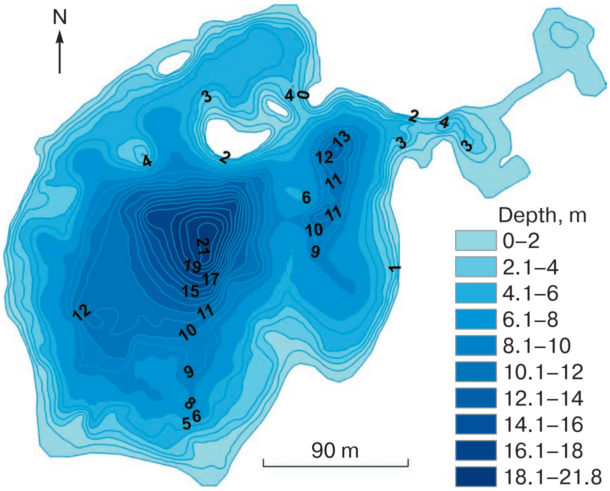

Fig. 4. Bathymetric map of Lower Bodomdara Lake (July 31, 2020).

The debris cone in the mouth of the Bodomdara River and the section of the Shakhdara River floodplain downstream the confluence with the Bodomdara River are insignificantly developed areas. In the Shakhdara River valley, numerous fragments of the Khorog–Pamir highway, including bridges over the Shakhdara River, individual buildings, and numerous agricultural lands downstream the mouth of the Bodomdara River are under threat of a possible outburst flood.

MATERIALS AND METHODS

To identify potential flood zones in the valleys of the Bodomdara and Shakhdara rivers, the following studies were carried out:

(1) field survey of the valley, bathymetric survey of the Lower lake, and survey of the debris cone of the Bodomdara River (Aga Khan Agency for Habitat (AKAH));

(2) data analysis, including interpretation of satellite images for different time periods, development of outburst scenarios, and construction of digital elevation model (DEM) for further modeling;

(3) outburst modeling actually, including (a) Lower Bodomdara Lake outburst simulation [*Vi-*

nogradov, 1976], (b) calculation of sediment increment in the area of a potential debris flow source using the transport-shift model [*Vinogradova, Vinogradov, 2017*], and (c) zoning of the Bodomdara valleys using hydrodynamic model FLO-2D [*O'Brien et al., 1993*].

In this study, we used archival satellite data *[https://services.arcgisonline.com/ArcGIS/rest/services/World_Imagery/MapServer; https://earthexplorer.usgs.gov/]* and new field materials. The bathymetric survey of Lower Bodomdara Lake was performed on July 31 by the AKAH team from a motor inflatable boat with a Lowrance Hook 5 echo sounder. The length of the water routes was about 4 km. Most of the lake area was covered by measurements. Sentinel-2 image from August 6, 2020 was used to correct the shoreline of the lake [*https://apps.sentinel-hub.com/eo-browser/*]. The survey of the Bodomdara River valley debris cone was also carried out by the AKAH team using a SenseFly eBee UAV.

The Agisoft Metashape Version 1.5.5 software package was used to process stereo images and create an orthophotoplan and a digital elevation model (DEM) of the territory. A large number of trees in the lower reaches of the Bodomdara River led to the appearance of a "levee" on the DEM. The use of machine learning methods allowed the Agisoft Metashape program to automatically classify a dense cloud of points into several classes. A classification was carried out for the "high vegetation" class. All classes were used in the construction of the DEM.

Software packages Reef Master v. 1.8.41 (viewing and visualization of echolocation data, saving of initial data of echograms) and ArcGIS 10.8.5 (processing and visualization of initial and final data) were used to process materials and build a bathymetric map.

Computational scenarios for modeling. Two scenarios of the development of an outburst flood were considered, and a set of mathematical models were used for the calculation (Fig. 5). In scenario I, the formation of an outburst flood from Lower Bodomdara Lake was assumed. The current volume of the lake (328,000 m^3) was taken into account to calculate the hydrograph of the lake outburst according to the outburst model for a lake dammed by a glacier proposed by Yu.B. Vinogradov [*Vinogradov, 1976, 1977*] was used. Then, this hydrograph was used in the transport-shift model of debris flow formation [*Vinogradov, Vinogradova, 2010*], modernized by the authors [*Iudina (Kurovskaia) et al., 2022*] to calculate sediment increment in the potential debris flow source. The obtained hydrograph was used to find the depth and velocity of the debris flow using two-dimensional hydrodynamic model FLO-2D [*O'Brien et al., 1993*].

Scenario II assumed a cascade outburst flood of Upper and Lower Bodomdara lakes with the maximum possible water accumulation of 700,000 m^3 in case of overflow through the dam of Lower lake. The discharge of the outburst flood for this scenario was obtained according to the formula [*Huggel et al., 2004*] and was equal to 430 m^3/s. It was then used as input hydrological data in the transport-shift model. The hydrograph calculated in the transport-shift model was used for zoning the valley in FLO-2D.

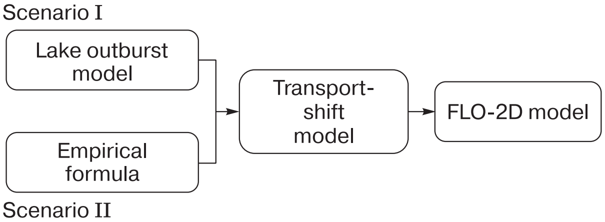

Fig. 5. A scheme of the set of mathematical models used for scenarios I and II of the outburst flood development.

This paper does not consider a scenario, in which the flow from the Darmaidovan River blocks the Bodomdara River with the formation of a new dammed lake. Though this scenario is unlikely, it cannot be excluded. Additional research is required for its consideration. Also, when modeling, the probability of a collapse into the lake is not considered separately. The prerequisites for this collapse are created by an unstable block of rocks in the upper part of the glacier cirque in the center. Satellite images show rock falls on both sides at the end of the hanging glacier, which indicates a possible removal of an unstable block of rock in the future, possibly with a certain amount of ice of about one million cubic meters in volume. When such a block falls, an ice–stone avalanche will inevitably occur and block the upper lake; in summer, this can lead to its splash and subsequent cascade process involving the lower lake. A similar case occurred recently in Peru and was described in [*Vilca et al., 2021*]. This scenario is not considered in this paper, since the main goal was to assess potential flooding zones in the valleys of the Bodomdara and Shakhdara rivers using a set of mathematical models. The model scenarios take into account the outburst of Lower Bodomdara Lake through subglacial runoff channels and the cascade outburst of lakes with the erosion of the dam of the lower lake.

Lake outburst model. Based on the analysis of materials on lake outbursts in various regions of the world, Yu.B. Vinogradov concluded that the outburst of glacial lakes takes place not only because of the destruction of the ice dam but also because of the appearance and expansion of englacial channels [*Vinogradov, 1977*]. Indeed, modern studies confirm that outbursts of glacial lakes can be connected with the formation of englacial channels [*Huss et al., 2007; Hewitt, Jingshi, 2010; Erokhin et al., 2018; Bhambri et* *al., 2020; Che et al., 2022*]. This mechanism can be concluded from the negative asymmetry of recorded hydrographs of the outburst [*Vinogradov, 1977*]. The processes of lake outburst in such cases begin with a relatively slow increase in the outflow of water, reaching a maximum and then a sharp decline [*Huss et al., 2007; Vinogradov, Vinogradova, 2008*].

Despite the fact that Lower Bodomdara Lake is dammed not by a glacier, but by a moraine with an ice core, the authors believe that the presence of buried cracks makes it possible to use this model. Geomorphological analysis of the Darmaidovan River valley allows us to conclude that, apparently, the outburst of Lower Bodomdara Lake will first go through the buried runoff channels and then come to the surface. A similar situation was observed during the outbursts of Lake Teztor (Kyrgyzstan) in 1953 and 2012, when the stream initially formed the way through englacial runoff channels and came to the surface 400 m downstream [*Erokhin et al., 2018*].

Vinogradov's mathematical model of lake discharge is based on the equations of the development of an englacial tunnel linking into a single process the decline in the lake water level, the flow discharge, the water temperature, the appearance of the tunnel, its length, and the difference in heights [*Vinogradov, 1976*]. The works [*Vinogradov, 1976; Vinogradov, Vinogradova, 2008*] present a comparison of the modeled and observed values on the examples of outbursts of large glacial lakes in Iceland (Lake Grimsvetn, 1922, 1934, 1945; Lake Grenaloun, 1935, 1939), British Columbia (Lake Talsekva, 1958), Tajikistan (Lake Medvezhye, 1973), and the USA (Lake George, 1951). In general, the model showed sufficient agreement with the recorded hydrographs.

The model was adapted when calculating the presumptive outburst of Bashkara Lake in the Central Caucasus according to a study of the lake in 2003–2007 [*Gnezdilov et al., 2007*]. The model was also used to calculate outbursts of glacial and subglacial reservoirs of Antarctica [*Popov et al., 2019*]. In the first case, the model was written in the Fortran programming language. In the second the Delphi language was applied, but it was not published in the public domain.

If the water temperature in the lake regulated by the presence of an ice dam and floating icebergs is zero, the flow rate of the outburst flood is as follows:

$$Q=\delta\left\{\frac{\rho_0 g}{\rho r l}\left[h\left(W_0-W\right)+\frac{a}{m+1}\left(W_0^{m+1}-W^{m+1}\right)\right]\right\}^{5/4}\times$$
$$\times\sqrt{aW^m}, \tag{1}$$

where ρ_0 is the density of water, 1000 kg/m^3; ρ is the density of water–ice mixture, 850–910 kg/m^3; g is the acceleration of gravity, 9.81 m/s^2; r is the specific heat of ice melting, 334,000 J/kg; l is the length of the tunnel, m; h is the difference in heights between the entry and exit points of the tunnel, m; W_0 is the volume of water in the lake before the outburst, thousand m^3; a, m are morphometric parameters of the lake bowl determined from the equation $H = aW^m$, H is the water level in the lake; W is the volume of water in the lake; and δ is an empirical coefficient depending on the length of the tunnel. The maximum water discharge of the outburst flood will be at W, at which the following equality is fulfilled:

$$W_0\left(h+\frac{a}{m}W_0^m\right)=$$
$$=W\left[\left(\frac{2.5}{m}+1\right)h+\frac{a}{m+1}\left(\frac{2.5}{m}+3.5\right)W^m\right]. \tag{2}$$

In the case of a significant difference of lake water temperature from 0 °C, the following equations should be used [*Vinogradov, 1977*]:

$$Q=\delta\left\{\frac{\rho_0 g}{\rho r l}\left[\left(x+h\right)\left(W_0-W\right)+\frac{a}{m+1}\left(W_0^{m+1}-W^{m+1}\right)\right]\right\}^{5/4}\times$$
$$\times\sqrt{aW^m}; \tag{3}$$

$$x=\frac{C_0}{g}t\left\{1-\exp\left[-\frac{400\delta^{0.3}l\left(aW^m\right)}{Q^{0.55}\rho_0 C_0}\right]^{0.15}\right\}, \tag{4}$$

where C_0 is the specific heat capacity of water, 4190 J(kg·°C); and t is the temperature of water in the lake, °C.

According to our estimates, the length of the subglacial channel in the case of the Lower Bodomdara Lake outburst may reach 732 m. The water temperature in the lake was estimated at 2.5 °C. Morphometric parameters of the lake bowl – a and m obtained from the bathymetric survey data – were 0.061 and 0.65, respectively.

The solution of model equations (1)–(4) was implemented in the Python programming language and connected with an upgraded transport-shift model of debris flow formation.

Transport-shift model of debris flow formation. The model equations were developed by Yu.B. Vinogradov on the basis of experimental data on artificially generated debris flows in the Chemolgan River valley in 1971–1975. The debris flow discharges calculated using this model proved to be in agreements with observation data [*Vinogradova, Vinogradov, 2017*].

The PALSAR DEM (cell size 12.5 m) was used as the basis for relief modeling. The characteristics of debris flow-forming soils, such as the angle of internal friction and the ratio of the volume of water to the volume of solid substance, were used the same for both scenarios and were evaluated on the basis of regulating documents [*SP 425.1325800.2018*], engineering and geological survey materials form the Sevkavgiprovodkhoz Institute [*Nikulin, 2009*] and the works of Yu.B. Vinogradov [*Vinogradov, Vinogradova, 2010*]. In the case of an outburst of the lower lake, the potential debris flow source was supposed to be allocated to moraine in the upper reaches of the Darmaidovan River. The average slope was 13° (Fig. 6). For scenario II, a cascade outburst of the Bodomdara lakes was assumed to be the result of the overflow and/or destruction of the lake dam. In this case, data from the recharge site upstream the left tributary outflow cone were taken into account. This site also represented moraine sediments (Fig. 6). The average slope was 14.8°.

Hydrodynamic model FLO-2D. The FLO-2D model is a two-dimensional model based on the numerical solution to the Saint-Venant equations based on regular rectangular computational grids. When modeling the movement of debris flow in the FLO-2D model, it is assumed that debris flows move like a Bingham fluid (viscoplastic fluid) [*O'Brien et al., 1993*]. The basic equation of the model is the equation for calculating the friction slope [*O'Brien et al., 1993*].

To use 2D models, detailed information about the morphometry of river valleys is required, which is presented in the form of a field of points. Thus, we obtain a picture of the distribution of flow velocities, water levels, and water depths within the calculated area.

The PALSAR DEM was main source of information on the relief of the territory. The position of riverbeds was refined using satellite images. For the Shakhdara River, data from topographic maps on a scale of 1:50 000 were used to model the relief, because the PALSAR DEM for this area contained serious errors in the narrowest places of the river valley with high rocky slopes. After necessary corrections, the relief data were interpolated into the model grid with the cell size of 12.5 × 12.5 m. The UAV survey was used to construct the relief for the Bodomdara River cone with a high quality of detail. The resolution of the original digital elevation model was 1 m. The most probable parameters of debris flows were determined based on the materials of previous studies [*Petrakov et al., 2012*]. The sediment content in the debris flow was assumed to be 30–35%.

The study area downstream the lakes was divided into 5 sections (Fig. 6): (1a) the upper section of the potential debris flow source according to scenario I (the length of the section was 225 m); (1b) the upper section of the potential debris flow recharge site according to scenario II (84 m); (2) the section from the debris flow source to the alluvial cone of the Bodomdara River (the flow through this section was considered as a debris flow with the water discharge of Bodomdara River set to 5 m^3/s; the length of this section was 27 km); (3) the section for the alluvial cone of the Bodomdara River with a detailed topography obtained during the UAV survey; the flow in this section was considered as debris flow for the Bodomdara River and as water flow with the discharge of 30 m^3/s for the Shakhdara River; the length of this section was 2.4 km; (4) the section of the Shakhdara River downstream the Bodomdara cone to the confluence of the Dasht River (the water flow discharge for this section was set at 30 m^3/s; the length of this section was 18.4 km); and (5) the section of the Shakhdara River from the confluence of the Dasht River to the mouth (water discharge was equal to 30 m^3/s; section length 27.2 km).

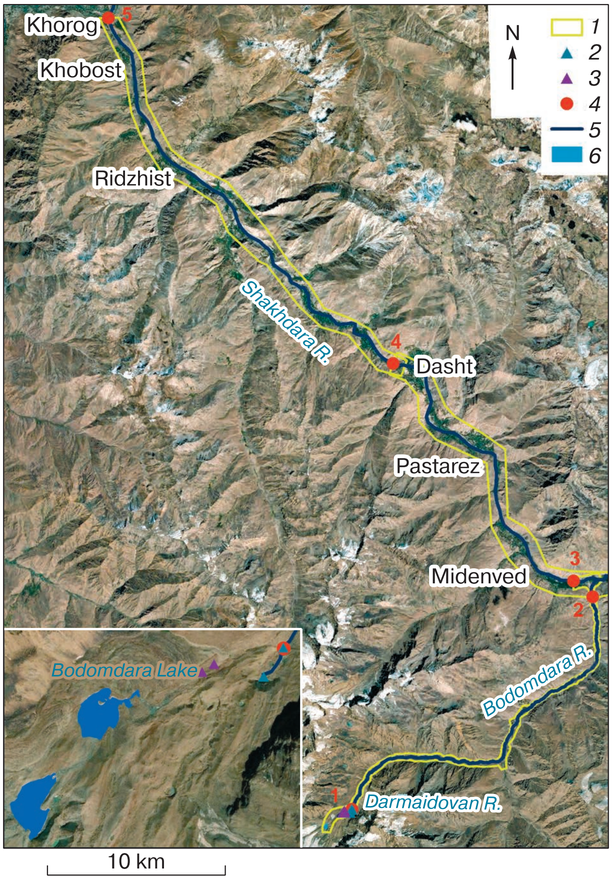

Fig. 6. Simulation scheme of possible outburst floods.

(*1*) boundaries of FLO-2D modeling, (*2*) boundaries of a potential debris flow source (scenario I), (*3*) boundaries of the recharge site (scenario II), (*4*) gauges for calculating hydrographs according to FLO-2D, (*5*) rivers, and (*6*) lakes.

RESULTS OF MODELING OUTBURST FLOODS AND DEBRIS FLOWS

According to scenario I, an outburst of Lower Bodomdara Lake with a volume of 328,000 m^3 (the

Table 2. **The results of an outburst flood simulation according to lake outburst and transport-shift models**

Scenarios	Outburst volume, m^3	Maximum discharge of the outburst flood, m^3/s	Maximum discharge of the debris flow wave, m^3/s	Lag time, h
I	328,000	167	459	0.96
II	700,000	430	840	0.40

current volume of the lake) takes place. The maximum discharge of the outburst flood calculated using the lake outburst model [*Vinogradov, 1977*] should reach 167 m^3/s and be observed 57 min after the beginning. The debris flow discharge at the debris flow source calculated according to the transport-shift model should increase to 459 m^3/s (Table 2), and the debris flow density, to 1637 kg/m^3. The average debris flow velocity at the debris flow source should be 6.1 m/s.

Scenario II assumes a cascade outburst of the Bodomdara lakes with a total volume of 700,000 m^3. The maximum discharge of the outburst flood, according to the formula [*Huggel et al., 2004*] should be 430 m^3/s. The shape of the input hydrograph was assumed to be almost symmetrical, with a maximum 24 min after the start and the total duration of 0.8 h. After passing the potential debris flow recharge site, the discharge should reach 840 m^3/s (according to the transport-shift model); the debris flow density should be 1489 kg/m^3 and the average flow velocity, 7.2 m/s.

The FLO-2D hydrodynamic model was used to obtain flood depths, flow velocities, and lag time in the valley for both scenarios of outburst flood. Hydrographs obtained in the transport-shift model of debris flow formation were used as input hydrological data. According to the simulation data, the lag time of the debris flow from the debris flow source to the alluvial cone of the Bodomdara River should be 1.67 h in scenario I and 1.37 h in scenario II (Fig. 7). The maximum water discharge at the top of the alluvial cone will be 143 m^3/s at the input discharge of 459 m^3/s and 348 m^3/s at an input discharge of 840 m^3/s.

In the Bodomdara River valley, the largest depths and flow velocities should be observed during the outburst flood passage. Under all scenarios, the flow velocities over a larger part of the channel will be 1.5–5.0 m/s and even more in some sections. The flow depths in the channel can reach 0.5–7.7 m. However, there are no infrastructure facilities and settlements in this valley, so the danger of such flood is only a potential threat.

On the alluvial cone, the flow will spread evenly over the surface. Under scenario I corresponding to lake volume in 2020, the flow depth in the Bodomdara channel may reach will reach 2 m and, in the Shakhdara channel, 4.6 m (Fig. 8*a*).

The flow velocities on the alluvial cone should not exceed 1.6 m/s. In the channels of the Bodomdara and Shakhdara rivers, they may vary from 3 to 5 m/s.

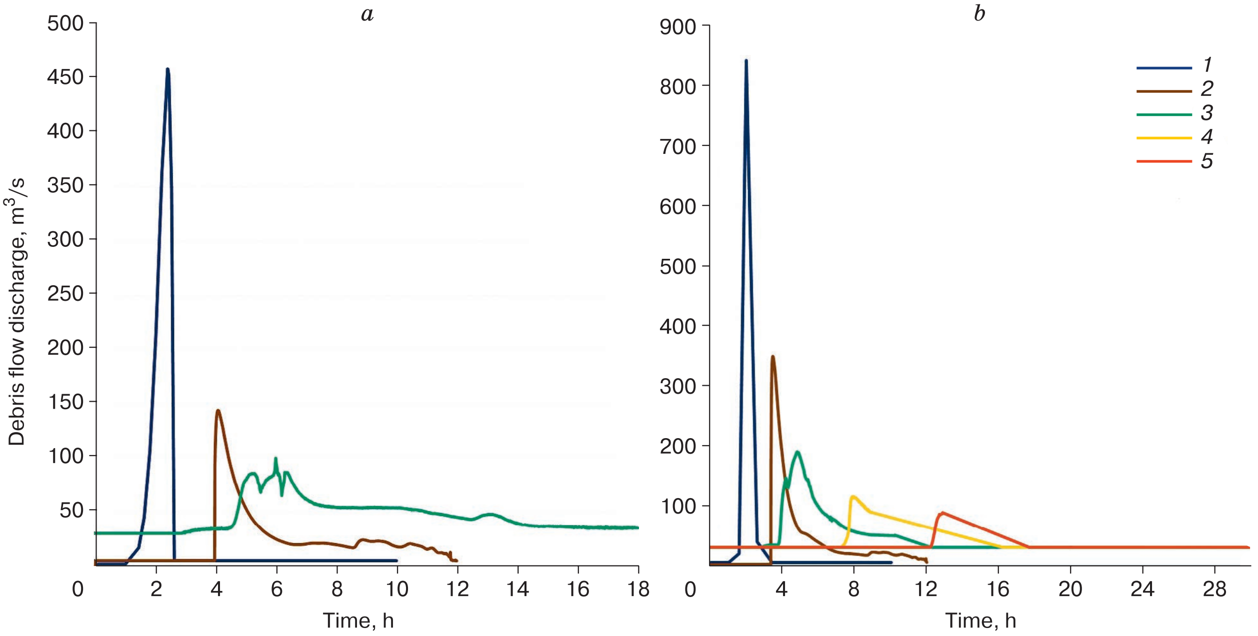

Fig. 7. Hydrographs of the outburst flood obtained from simulation according to (*a*) scenario I (outburst volume 328,000 m^3) and (*b*) scenario II (outburst volume 700,000 m^3).

(*1*) at the exit from the debris flow source, (*2*) at the top of the cone of the Bodomdara River, (*3*) the Shakhdara River downstream the Bodomdara cone, (*4*) the Shakhdara River downstream the cone of the Dasht River, (*5*) the Shakhdara River at the confluence with the Gunt River.

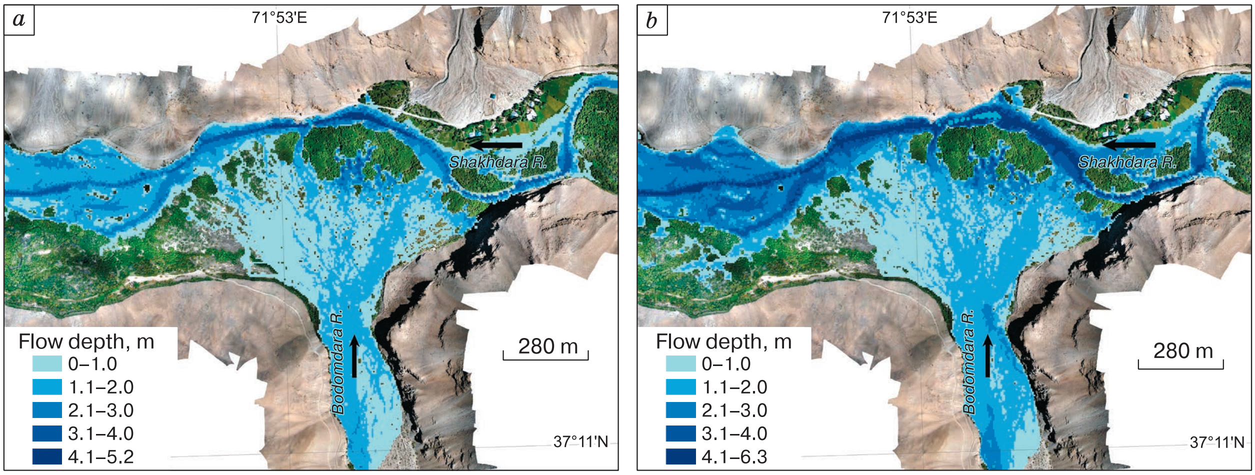

Fig. 8. Depths of flooding at the mouth of the Bodomdara River according to the results of FLO-2D modeling on detailed topographic data from UAV survey for (*a*) outburst scenario I and (*b*) outburst scenario II.

Downstream the alluvial cone, the hydrograph of the Shakhdara River should have a flattened shape due to the flow spreading; the peak of the flood will be observed in 5.2 h from the moment of the outburst, and the maximum discharge, taking into account the input discharge of the Shakhdara River (30 m^3/s) will reach 86 m^3/s, which is significantly lower than the discharge under scenario II (188 m^3/s). In this regard, the movement of the outburst flood under scenario I downstream the Shakhdara valley was not considered.

Under the hypothetical scenario II, taking into account the outburst flood of a larger volume, the depth of the flood in some areas of the alluvial cone can exceed 4 m, areas with flow velocities up to 5 m/s will be formed in the central and upper parts of the cone (Fig. 8*b*).

The maximum discharge of the Shakhdara River downstream from the Bodomdara cone will be observed in 4.8 h after the outburst and will reach 188 m^3/s. The alluvial cone of the Bodomdara River and the downstream section of the Shakhdara River floodplain are currently developed to a small extent; there are no buildings in the potential flood zone. Upstream the Bodomdara alluvial cone, on the right bank of the Shakhdara River, there are houses of the village of Otzhaga, which may be flooded in the case of damming of the Shakhdara River by the debris flow.

According to scenario II, when moving along the Shakhdara valley for 50 km to the mouth of the river, the flood will spread significantly; the maximum discharge in the middle of the section near the cone of the Dasht River and the village of the same name will be 114 m^3/s; the flood wave will reach this gauge is 7.92 h. In the mouth of the Shakhdara River, the wave of the outburst flood will reach a maximum in 13 h after the lake outburst. The maximum discharge at the mouth of the Shakhdara River will reach 89 m^3/s (taking into account the base discharge of 30 m^3/s), which will exceed the maximum discharge of 48.6 m^3/s observed at the gauge station in the village of Khabost (at the mouth of the river) [*Surface..., 1971*]. It is worth noting that most settlements along the Shakhdara River in its lower reaches are located at fairly high levels relative to the water level; however, flooding of houses and other buildings in close proximity to the river with the flow depth varying from 0.3 to 1.0 m can be observed. To obtain more accurate results, it is necessary to use detailed topographic data for each locality. It is important that any economic activity (pasturing, haymaking, etc.) in the floodplain areas is potentially endangered by the in outburst flood in the considered areas.

CONCLUSIONS

Possible causes and consequences of an outburst flood in the Bodomdara River valley have been estimated using data from detailed field studies. When comparing the location of the edges of the active glacier tongues on satellite images of 2008 and 2020, the retreat of the glacier by 50–120 m in 12 years (i.e., up to 10 m/yr) has been determined. The edge of the glacial-moraine complex is stable, but the ice wall above the river source has also noticeably retreated (by 35–40 m in 12 years; 3 m/yr). The degradation of the glacier leads to the changes in dynamics of glacial lakes and their dams. Thus, Upper Bodomdara Lake has appeared in recent decades. The supraglacial position of this lake suggests a possibility of its outburst as a result of the retreat of the glacier and the damage of the ice dam. In turn, this will trigger an outburst of Lower Bodomdara Lale with the development of cascade outburst flood. Though the bowl-shaped depression of the lower lake is relatively stable, its outburst is possible without a cascade flood at abnormally high temperatures and intense snowmelt combined with extreme rainfall.

For the first time, an integration of three mathematical models has been used to model outburst floods : the model of lake outburst through englacial channel by Yu.B. Vinogradov, the transport-shift model by Yu.B. Vinogradov, and the FLO-2D hydrodynamic model.

Two scenarios of an outburst flood were considered: (I) outburst of Lower Bodomdara Lake with a volume of 328,000 m^3 and (II) cascade outburst of both lakes with a total volume of 700,000 m^3. For scenario I, the maximum discharge of the outburst flood obtained using bathymetric lake survey data and lake outburst model by Yu.B. Vinogradov may reach 167 m^3/s. Further estimate of sediment material increment at the potential debris flow source has been carried out using a transport-shift model of debris flow formation; the predicted discharge of the debris flow may reach 460 m^3/s. A two-dimensional hydrodynamic model FLO-2D with a debris flow block has been adapted to the section of the outburst flood movement along the Darmaidovan, Bodomdara, and Shakhdara rivers with a total length of 75 km. This adapted model has been used to estimate the depth of the flood, flow velocities, potential danger of the flood, and the lag time of the maximum flood wave after the outburst flood. According to the results of hydrodynamic modeling, at the top of the alluvial cone of the Bodomdara River, the maximum flow discharge will be 143 m^3/s; it will be reached in 4.07 h after the outburst of the lake. The maximum discharge of the Shakhdara River downstream the cone will be 86 m^3/s.

The maximum discharge of the outburst flood according to scenario II as calculated using the formula [*Huggel et al., 2004*] will be 430 m^3/s. After the additional increment at the debris flow recharge site, it will reach 840 m^3/s. At the top of the alluvial cone of the Bodomdara River, the maximum flow discharge will be 348 m^3/s, and it will be reached in 3.47 h after the start of the outburst. The flow velocities will reach 3 m/s, and the flow depth will reach 4 m. The maximum flow discharge in the Shakhdara River downstream the Bodomdara alluvial cone will be 188 m^3/s; at the river mouth (50 km downstream), it will decrease to 89 m^3/s. These discharges in the lower reaches of the Shakhdara River are three times higher than the maximum recorded water discharges. Despite the fact that most of the settlements in the Shakhdara River valley are located at fairly high elevations beyond the flood prone zone, the bridges of the Khorog–Pamir highway across the Shakhdara river are at risk. Meadows and pastures and outbuildings within them, as well as individual houses located on the banks of the river are in the flood prone zone. The greatest damage can be expected in the area of the villages of Bidizi Bolo, Anbaz/Vezdara, Tsorzh, and Midenved. A damage to buildings and lands of the village of Otzhaga on the right bank of the Shakhdara River immediately upstream the mouth of the Bodomdara River is also possible because of the damming effect of the debris flow as a result of river bank erosion and flooding.

Taking into account the unfavorable dynamics of the glacial-moraine complex, the further growth of the upper lake and the possible breach of the lower lake dam, regular remote monitoring of the situation in the upper reaches of the Darmaidovan River is necessary. Planning of economic activity in the valleys of the Bodomdara and Shakhdara rivers below the mouth of the Bodomdara River should be carried out taking into account the possibility of an outburst flood wave passing here.

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References

Bhambri R., Watson C.S., Hewitt K. et al., 2020. The hazardous 2017–2019 surge and river damming by Shispare Glacier, Karakoram. *Sci. Rep.* **10** (4685). DOI: 10.1038/s41598-020-61277-8.

Cesca M., d'Agostino V., 2008. Comparison between FLO-2D and RAMMS in debris-flow modeling: a case study in the Dolomites. *WIT Transact. Engin. Sci.* **60**, 197–206. DOI: 2495/DEB080201.

Che Y., Wang S., Wei Y. et al., 2022. Rapid changes to glaciers increased the outburst flood risk in Guangxieco Proglacial Lake in the Kangri Karpo Mountains, Southeast Qinghai-Tibetan Plateau. *Nat. Hazards* **110**, 2163–2184. DOI: 10.1007/s11069-021-05029-5.

Dokukin M.D., Bekkiev M.Yu., Kalov R.Kh. et al., 2020. Rock glaciers as origination sites of the catastrophic debris flows. *Georisk* **14** (2), 52–65 (in Russian).

Erokhin S.A., Zaginaev V.V., Meleshko A.A. et al., 2018. Debris flows triggered from non-stationary glacier lake outbursts: the case of the Teztor Lake complex (Northern Tian Shan, Kyrgyzstan). *Landslides* **15**, 83–98. DOI: 10.1007/s10346-017-0862-3.

Glazyrin G., Braun L.N., Shchettinnikov A.S., 2018. Sensitivity of mountain glaciation erization to climate changes in Central Asia. *Zeitschrift fuer Gletxcherkunde. Glazialgeol.* **39**, 71–76.

Gnezdilov Yu.A., Ivaschenko E.N., Krasnykh N.Yu., 2007. Assessment of the hypothetical outburst of Lake Bashkara. In: *Collection of Scientific Works of JSC Sevkavgiprovodkhoz*, Pyatigorsk, **17**, pp. 122–145 (in Russian).

Iudina (Kurovskaia) V.A., Chernomorets S.S., Vinogradova T.A., Krylenko I.N., 2022. Modeling of debris flow triggered by snow melting: case study of the Barsemdara River, Tajikistan. *Earth's Cryosphere* **26** (3), 43–53.

Harrison S., Kargel J.S., Huggel C. et al., 2018. Climate change and the global pattern of moraine-dammed glacial lake outburst floods. *The Cryosphere* **12** (4) 1195–1209. DOI: 10.5194/tc-12-1195-2018.

Hewitt K., Jingshi L., 2010. Ice-dammed lakes and outburst floods, Karakoram Himalaya: historical perspectives on emerging threats. *Physical Geogr.* **31** (6), 528–551.

Huggel C., Haeberli W., Kääb A. et al., 2004. An assessment procedure for glacial hazards in the Swiss Alps. *Can. Geotech. J.* **41** (6), 1068–1083.

Huss M., Bauder A., Werder M. et al., 2007. Glacier-dammed lake outburst events of Gornersee, Switzerland. *J. Glaciol.* **53** (181), 189–200. DOI: 10.3189/172756507782202784.

Hutter K., Svendsen B., Rickenmann D., 1994. Debris flow modeling: A review. *Continuum Mech. Thermodyn.* **8**, 1–35.

Jan C.D., Shen H.W., 1997. Review dynamic modeling of debris flows. In: Armanini A., Michiue M. (Eds.), *Recent Developments on Debris Flows. Lecture Notes in Earth Sciences*, vol. 64. Springer, Berlin, Heidelberg. DOI: 10.1007/BFb0117764.

Jansky B., Engel Z., Sobr M. et al., 2009. The evolution of Petrov Lake and moraine dam rupture risk (Tien-Shan, Kyrgyzstan). *Natural Hazards J.* (1), 83–96.

J-42-108 (Roshtkala). Topographic Map, Scale 1:100 000. Joint Staff, Moscow, 1988.

Kääb A., Huggel C., Fische L. et al., 2005. Remote sensing of glacier- and permafrost-related hazards in high mountains: an overview. *Nat. Hazards Earth Syst. Sci.* **5**, 27–554. DOI: 10.5194/nhess-5-527-2005.

Kidyaeva V.M., Chernomorets S.S., Savernyuk E.A. et al., 2020. Outburst-hazardous lakes in the Gunt River basin (Gorno-Badakhshan Autonomous Region, Tajikistan): hazard assessment and outburst modeling. In: *Avalanches, Debris flows and Risk Assessment*. Moscow, Pero, pp. 18–43 (in Russian).

Khromova T.E., Osipov G.B., Tsvetkov D.G. et al., 2006. Changes in glacier extent in the eastern Pamir, Central Asia, determined from historical data and ASTER imagery. *Remote Sens. Environ.* **102** (1–2), 24–32.

Khromova T., Nosenko G., Kutuzov S. et al., 2014. Glacier area changes in Northern Eurasia. *Environ. Res. Lett.* **9** (1), 015003.

Komatsu T., Watanabe T., 2014. Glacier-related hazards and their assessment in the Tajik Pamir: A short review. *Geograph. Studies* **88** (2), 117–131.

Kotlyakov V.M., Dyakova A.M., Koryakin V.S. et al., 2011. *Glaciers of the Former Soviet Union. Glaciers of Asia*, U.S. Geol. Survey Prof. Paper 1386–F, 349 pp.

Luknitsky P.N., 1955. *Travels in the Pamir.* Moscow, Molodaya Gvardiya, 502 pp. (in Russian).

Mergili M., Müller J.P., Schneider J.F., 2013. Spatio-temporal development of high-mountain lakes in the headwaters of the Amu Darya River (Central Asia). *Glob. Planet. Change* **107**, 13–24.

Mergili M., Schneider J.F., 2011. Regional-scale analysis of lake outburst hazards in the southwestern Pamir, Tajikistan, based on remote sensing and GIS. *Nat. Hazards Earth System Sci.* **11**, 1447–1462.

Mergili M., Schneider D., Worni R. et al., 2011. Glacial lake outburst floods in the Pamir of Tajikistan: Challenges in prediction and modeling. Proc. 5th Intern. Conf. *Debris-Flow Hazards Mitigation: Mechanics, Prediction and Assessment* (Padua, June 14–17, 2011). Padua, Italy, pp. 973–982.

Mikhailov V.O., 2011. Classification of numerical mathematical models of debris flow and slope processes. *Inzhenern. Geol.* **3**, 26–33 (in Russian).

Mikhailov V.O., Chernomorets S.S., 2011. *Mathematical Modeling of Debris flows, Collapses and Landslides*. Moscow, Lambert, 131 pp. (in Russian).

Nikulin A.S., 2009. Experience in determining the angles of internal friction of debris flow clay. In: *Collection of Scientific Works of JSC Sevkavgiprovodkhoz* **18**, 30–33 (in Russian).

O'Brien J., Julien P., Fullerton W., 1993. Two-dimensional water flood, debris flow simulation. *J. Hydraul. Engin.* **119** (2), 244–259.

Petrakov D.A., Tutubalina O.V., Aleinikov A.A. et al., 2012. Monitoring of Bashkara Glacier lakes (Central Caucasus, Russia) and modelling of their potential outburst. *Nat. Hazards* **61** (3), 1293–1316. DOI: 10.1007/s11069-011-9983-5.

Popov S.V., Pryakhina G.V., Boronina A.S., 2019. Estimation of water discharge during development of glacial and subglacial outburst floods. *Earth's Cryosphere* **23** (3), 20–26.

Quincey D.J., Richardson S.D., Luckman A. et al., 2007. Early recognition of glacial lake hazards in the Himalaya using remote sensing datasets. *Glob. Planet. Change* **61** (1–2), 0–152.

Surface Water Resources of the USSR: Hydrological Study. Vol. XIV. Basins of the Rivers of Central Asia. Iss. 3. Amu Darya Basin. Leningrad, Gidrometeoizdat, 1967, 322 pp. (in Russian).

Surface Water Resources of the USSR. vol. XVI. Central Asia. Iss. 3. Amu Darya Basin. Leningrad, Gidrometeoizdat, 1971, 472 pp. (in Russian).

SP 425.1325800.2018, 2019. *Engineering Protection of Territories from Erosion Processes. Design Rules*. Moscow, Standartinform, 36 pp. (in Russian).

URL: https://earthexplorer.usgs.gov/ (date accessed: Sept. 8, 2021, date of issue: Sept. 13, 1975).

URL: https://earthexplorer.usgs.gov/ (date accessed: Sept. 8, 2021; date of issue: Aug. 20, 2010).

URL: https://apps.sentinel-hub.com/eo-browser/ (date accessed: Sept. 15, 2021; date of issue: 2015–2021).

URL: https://services.arcgisonline.com/ArcGIS/rest/services/World_Imagery/MapServer (date accessed: Sept. 1, 2021; date of issue: Sept. 10, 2013).

Vilca O., Mergili M., Emmer A. et al., 2021. The 2020 glacial lake outburst flood process chain at Lake Salkantaycocha (Cordillera Vilcabamba, Peru). *Landslides* **28**, 2211–2223. DOI: 10.1007/s10346-021-01670-0.

Vinogradov Yu.B., 1976. Method for calculating flood hydrograph in case of outburst of a glacier-dammed lake. In: *Debris Flows*. Moscow, Gidrometeoizdat, Iss. 1, pp. 138–153 (in Russian).

Vinogradov Yu.B., 1977. *Glacial Outburst Floods and Debris flows*. Leningrad, Gidrometeoizdat, 154 pp. (in Russian).

Vinogradov Yu.B., 1980. *Etudes about Debris Flows*. Leningrad, Gidrometeoizdat, 160 pp. (in Russian).

Vinogradov Yu.B., Vinogradova T.A., 2008. *Modern Problems of Hydrology*. Moscow, Academy, 320 pp. (in Russian).

Vinogradov Yu.B., Vinogradova T.A., 2010. *Mathematical Modeling in Hydrology.* Moscow, Academy, 304 pp. (in Russian).

Vinogradova T.A., Vinogradov A.Yu., 2017. The experimental debris flows in the Chemolgan River basin. *Nat. Hazards* **88** (Suppl. 1), 189–198.

Voellmy A., 1995. Über die Zerstörungskraft von Lawinen, *Schweiz. Bauzeitung* **73** (12), 159–162.

Wang X., Ding Y., Liu S. et al., 2013. Changes of glacial lakes and implications in Tian Shan, central Asia, based on remote sensing data from 1990 to 2010. *Environ. Res. Lett.* **8** (4), p. 044052.

Wu Y.H., Liu K.F., Chen Y.C., 2013. Comparison between FLO-2D and Debris-2D on the application of assessment of granular debris flow hazards with case study. *J. Mount. Sci.* **10** (2), 293–304.

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