Assessment of potential damage in case of Upper Akkol Lake outburst (South-Eastern Altai, Russia)

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Abstract. Due to the gradual reduction of glaciation area in high mountainous areas around the world, there is an active transformation of landscapes freed from ice. Namely, the number of glacial moraine-dammed lakes is increasing. Such lakes are often unstable, rapidly changing their morphometric characteristics, which requires observation. It is also known that recently there have been more frequent cases of catastrophic outbursts of such lakes and flooding of the territories below. Populations living in such areas are exposed to significant and often uncontrollable risks. One of such lakes, representing a potential threat of breaching, is the Upper Akkol Lake, located on the slope of the South Chuysky Ridge in South-Eastern Altai (Russia, Altai Republic).

In this article, we assessed the potential damage from a possible lake outburst, and the information was communicated to local administrations in order to take timely measures to minimize damage or avoid a catastrophe.

1 Introduction

Due to global climatic trends, glaciation of the Russian Altai has been in steady regression for a century and a half, and the glaciers of the main glaciation centers show a decrease in mass and area. The process of modern glacier retreat in the Russian Altai is accompanied by the formation of glacial lakes, the number of which increases in proportion to the rate of glaciation reduction [1-3]. Analysis of satellite images has shown that some of the glacial lakes of the Akkol Valley (South-Chuya Ridge, Russian Altai) have significantly increased the area of their mirrors and continue to change morphologically, which is a sign of their instability and danger of breakthrough.

Glacial lake outbursts have already occurred in the Altai Mountains in 1998, 2000 and 2012, and have resulted in tangible economic and environmental losses. The most dramatic event was the bursting of the maashey moraine-pond lake on July 17, 2012. [4-5]. The breakthrough flood caused significant damage to the infrastructure of Ulagan District in the Altai Republic, in particular, four bridges on the Maashey and Chuya rivers were destroyed, and pasture and forest lands were also affected. The danger of such phenomena in...
2 Materials and Methods
The moraine complex that dammed the Upper Akkol Lake reaches a height of 80-124 meters. It is represented by a complex system of sickle-shaped moraine ridges that occupy the entire lower part of the valley for 1.5 km. The lithology of the moraine is quite diverse. A specific feature of the internal structure of the complex is the presence of blocks of buried "dead ice". Due to its melting, the moraine surface is complicated by numerous thermokarst depressions partially covered by small lakes. Water accumulates in the depressions due to melting of the buried ice forming the bottom and sides of the depressions, as well as runoff of melt and rainwater from the slopes of the catchments. The area of lake catchments is relatively small and amounts to 0.01-0.1 km².

Fig. 2. (a) Upper Akkol Lake at the initial stage of formation. Historical photo by V.V. Sapozhnikov, 1898, (b) modern lake view photo by P. Borodavko, 2020

Field geomorphological studies and comparative analysis of aerial and satellite data for some years (1952, 1966, 2012, 2020) indicate a significant activation of thermokarst processes within the moraine complex over the last 50 years. This process is observed against the background of a statistically significant temperature increase in the warm season (on average by 0.3°C over 10 years), while the winter temperature regime has not changed significantly [24]. The gradual increase in the area of the thermokarst lakes closest to Upper Akkol Lake led to their merging into a single water body and the formation of a bay deeply cut into the moraine complex. Further development of thermokarst and thermoerosion processes in this part of the moraine complex will inevitably lead to the break of the moraine dam, which will cause a breakthrough flood (Fig. 2, 3).

Initially, to assess the potential damage from a mountain-glacial lake outburst, a predictive analysis of the magnitude of possible flooding was made by simulating the unsteady water movement using the flow hydrograph at the input sites of the models during the period of maximum water availability with a discreteness of 1 hour for 100 hours, i.e., a little more than 4 days. The results of observations showed that the maximum values of flow rate of the river Chagan in the vicinity of Beltir settlement are observed in July and averaged 25-35 m³/sec-1, the maximum discharge for the entire observation period was 65.5 m³/sec-1.

Discharges of the Taldura River are on average 60% of those of the Chagan River. The flow velocities of the Chuya River measured at the site near the Chagan-Uzun settlement during floods are 60-120 m³/sec-1.
Fig. 3. Spatial boundaries of the Upper Akkol Lake and thermokarst reservoirs of the terminal moraine complex of the Sofiyskiy Glacier. (a) in 1952; (b) in 1966; (c) in 2012; (d) in 2020. The red arrow shows the location of the presumed lake outburst.

Based on the obtained data, several scenarios of instantaneous discharges of the lake system with a volume of water of 7.3 m$^3$ into the Akkol River valley were modeled. The most unfavorable is the scenario of complete emptying of the entire lake system within four hours at a constant water flow rate of 492 m$^3$/s, which we adopted to calculate the scale of possible flooding and the consequences caused by it [6, 7, 8].

The mapping of possible scenarios was based on the creation of a digital elevation model (DEM). For this purpose, ASTER Global DEM remote sensing data, map material and satellite images from publicly available services were used. ASTER Global DEM data and cartographic materials were combined and refined in Autodesk Civil 3D software package. The merged and corrected DEM was exported for the HEC-RAS system in the same complex.

The obtained DEM was imported to the modeling system HEC-RAS version 5.0.7 into the RAS-Mapper tool built into the system of the program for work with GIS data, where with the help of the Geometric data tool the calculated grid of 2D cells was applied to the digital elevation model, parameters of roughness coefficients were set. Several variants of 2D-models were built both for separate sections of the Akkol, Chagan, Taldura, Chagan-Uzun and Chuya river valleys and for the whole section from the Upper Akkol lake to the Chuya river station below the Chagan-Uzun settlement. The length of the modeled section - Akkol, Chagan, Taldura, Chagan-Uzun and Chuya rivers is 60 km.
According to the results of modeling under the most unfavorable scenario, natural landscapes as well as populated areas with infrastructure facilities fall into the zone of maximum possible flooding. Hence, the potential total damage is calculated according to two components: loss of ecological functions of the natural environment, economic and social losses.

As a methodological basis for the assessment of potential damage to determine the cost estimate of costs of works and measures to prevent and eliminate the harmful effects of water is taken the methodology developed in 2006 by the Federal State Unitary Enterprise "All-Russian Research Institute for the Economics of Mineral Resources and Subsoil Use".

Specific basic indicators for determining the cost of damage from harmful (negative) impact of water were calculated in 2006 prices, taking into account the inflation rate based on the consumer price index according to statistic data for the Altai Republic for January 2023. The cost of some types of damages was determined by average market prices for goods and services in the study region at the end of 2022.

Expected economic damage is determined for the future as a possible (probable) damage on the state of social and economic development of the district in the absence of protective measures, taking into account the timely evacuation of the population and livestock. Cost indicators of expenditures on measures to prevent and eliminate the consequences of the breakthrough were calculated on condition of partial restoration of property of legal entities and individuals, health of citizens and costs associated with rescue operations, product losses, etc.

The total amount of economic damage from negative water impact, is determined by the formula:

\[ Y = Y_1 + Y_2 + Y_3 + Y_4 + Y_5 + Y_6 + Y_7 + Y_8 \]

where:

- \( Y_1 \) – damage from damage and disposal of fixed production assets (destruction of buildings, communications, structures, loss of machinery and equipment, washing away of perennial plantings, loss of livestock, etc.);
- \( Y_2 \) – damage to and disposal of current assets (raw materials, fuel, semi-finished products, seed stock, etc.);
- \( Y_3 \) – damage from loss of finished industrial and agricultural products;
- \( Y_4 \) – damage, including costs of emergency rescue operations and costs of evacuation of the population;
- \( Y_5 \) – damage from loss of personal property of citizens and property of the locality;
- \( Y_6 \) – damage, including costs of restoration of destroyed buildings, structures, communications, equipment;
- \( Y_7 \) – indirect damage, including damage from loss of lost profits due to loss of value of unsold industrial and agricultural products and profits and hence loss of taxes to the budget, both from trade and from enterprises and agricultural land directly damaged by flooding and inundation; Indirect economic damage occurs in related industries, it is caused by the downtime of enterprises processing the products of facilities damaged by flooding and inundation. Indirect damage also includes payment for the period of enterprise downtime, transportation losses, lost profits (loss of trade profit, taxes from related enterprises), etc. Indirect damage was calculated taking into account the coefficient from the amount of direct damage taken as the value of 0.02.
- \( Y_8 \) – other unrecorded damage also includes socio-economic damage, which is equal to the sum of losses of net product in the sphere of production due to increased morbidity of the population, increased payments from the social insurance fund for the period of temporary disability of workers, losses of deductions to social funds. This type of damage was calculated taking into account the coefficient 0.2 of the amount of direct damage.
3 Results

According to the most unfavorable scenario, in which at the section of Chagan river valley widening (1-6 km above Beltir settlement) the flow width increases up to 200-500 m, depths vary from 0.5-1.0 m to 2.5-3.5 m, and flow velocities increase from 2.0 to 4.0 m/sec in the flood zone of Beltir settlement, several houses appear in the flood zone of Beltir settlement.

Fig. 4. Flood zone near the village of Beltir at maximum flood discharge

In the narrow part of the valley of the Chagan-Uzun River, water levels at the flood peak rise by 1.0-2.0 m, and flow velocities more than double from 1.8-2.2 to 4.5-5.0 m/sec. In the river valley widening, the flow width increases up to 150-200 m, and in the widest places 400-500 m, maximum flow velocities increase from 1.3-1.5 to 2.5-3.0 m/sec. Water surface elevations at the flood peak near the Chagan-Uzun settlement increase by 1.3-1.5 m.

Consequently, about 134.5 thousand m$^2$ of the territory of Chagan-Uzun settlement may be under water. The main characteristics of the consequences of possible flooding of Upper Akkol Lake include both elements of the natural environment, the population in the flood zone, and infrastructure facilities (Table 1).

Table 1. Main characteristics of the consequences of possible flooding caused by the outburst of Upper Akkol Lake

<table>
<thead>
<tr>
<th>Indicators</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Population in the flood zone, persons</td>
<td>480</td>
</tr>
<tr>
<td>Number of settlements in the flood zone</td>
<td>2</td>
</tr>
<tr>
<td>Area of settlements in the flood zone, m$^2$</td>
<td>176 500</td>
</tr>
<tr>
<td>Number of residential houses in the flood zone</td>
<td>32</td>
</tr>
<tr>
<td>Area of residential houses in the flood zone, m$^2$</td>
<td>2250</td>
</tr>
<tr>
<td>Number of infrastructure facilities in the flood zone</td>
<td>6</td>
</tr>
<tr>
<td>Area of infrastructure facilities in the flood zone, m$^2$</td>
<td>2415</td>
</tr>
<tr>
<td>Length of roads in the flood zone (including intra-settlement roads), m</td>
<td>1625</td>
</tr>
</tbody>
</table>
Tourism facilities

<table>
<thead>
<tr>
<th>Facility Type</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earthen dam with structures, m</td>
<td>1180</td>
</tr>
<tr>
<td>Road bridges, m</td>
<td>205</td>
</tr>
<tr>
<td>Area of flooded agricultural lands (pastures), m²</td>
<td>882,000</td>
</tr>
<tr>
<td>Forest area, m²</td>
<td>245,200</td>
</tr>
</tbody>
</table>

In case of realization of the considered scenario in Beltir settlement, households located on the left bank of the Chagan-Uzun River will be in the flood zone. In addition, cattle breeding camps of local residents with temporary buildings—one in the valley of the Akkol River and three in the valley of the Chagan-Uzun River—will be affected. The flood zone also includes a school and a kindergarten, a medical and obstetric station, a police station, a yurt complex of six temporary structures Normad, guest house Sinegorye, a store, coastal fortification (flood protection) and tourist centers on the left bank of the Chagan-Uzun River.

Fig. 5. Flood zone near the village of Chagan-Uzun at maximum flood discharge

Also, from the significant engineering structures in the flood zone are two bridges near the village of Chagan-Uzun—wooden bridge for on-farm purposes (length 45 m), connecting the villages of Chagan-Uzun, Ortolyk and Stary Beltir. And the second bridge over the Chuya River at the mouth of the Chagan-Uzun River, the only capital bridge connecting the Chagan-Uzun settlement with the Chuya tract. Two bridges may be destroyed in Beltir settlement: over the Akkol River and the Chagan-Uzun River. It should be noted that the bridge over the Akkol River is located in the zone of maximum predicted flood depth, which suggests that a full restoration of the bridge, whose length in this case is 40 m, will be required.

Discussion

In case of unfavorable development of the situation as a result of the flood, the relic poplar grove at the mouth of the Chagan-Uzun River, coniferous forest at the foot of the Sukor mountain ledge downstream from the settlement will be affected. Chagan-Uzun and the habitat of the red-listed jumping gopher tortoise near Beltir settlement. Besides, the flood...
will wash away the valuable in paleo

geographical and stratigraphic respect object

ribbon

layered deposits in the valley of the Chagan-Uzun river, which now have excursion value, the object is widely known among the guests of the republic as "The Moon". The sediments are easily erodible, as they are composed of a thin fraction of clays and siltstones. The already impoverished soil cover will be significantly affected, its restoration will take many decades, the areas of pastures suitable for grazing will be sharply reduced.

The economic component of the total amount of damage in the forecast scenario will amount to about 768.64 million rubles, of which about 87% is the direct damage (Fig. 3).

Of the total amount of potential damage, the greatest specific weight is occupied by losses associated with dam failure and the costs of evacuation of the population, temporary construction and re-evacuation, as well as compensation payments to the population (Fig. 4).

Significant damage may be caused to the housing stock and the flooded territory of home

stead plots - 538,4 thousand of dollars. When restoring the affected territories of the settlements themselves, an amount of 514 thousand of dollars will be required, and 710,6 thousand of dollars will be needed to restore bridges.

It is possible to minimize the expected losses if a number of preventive measures are taken, both regulatory and preventive measures to protect the population from floods. Regulatory measures include water flow regulation works, dam inspections. Preventive measures consist of informing the population about the potential danger and the expected areas of flooding in the event of a breach.

5 Conclusion

High mountain lakes today carry serious hazards and threats of breakthrough floods that are disasters for people living nearby. It is important to know about such danger in advance, so such lakes require observation and study. A timely identified threat allows preventing flooding if possible or minimizing the damage by developing and minimizing a number of measures aimed at this in advance. The studied Upper Akkol Lake poses a real danger to the residents of the Altai Mountains. However, to date, the administration has been warned about it and a set of measures aimed at anticipating and preventing the lake breakthrough is under development, which will avoid damage and, most importantly, save lives.

6 Acknowledgments

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References


