A Brief Description of Methods
Used by the Institute of Geography and Water Security to Assess the Hazards and Risks from Glacier Lake Outburst Floods and Mudflows

According to the statistics, a large number of glacial mudflows in Kazakhstan were caused by the release of melted glacial waters from subglacial reservoirs (glacial runoff channels). At the same time, all cases of catastrophic glacial mudflows were caused by glacial lake outbursts [1-3, 6, 7]. Thus, the definition of "glacial mudflow hazard", due to the prevailing importance of lake outbursts in the statistics of mudflow disasters, almost completely corresponds to the term "outburst hazard" of glacial lakes, which has been widely used recently.

The methods for assessing the hazard of glacial lake outbursts (outburst hazard) and glacial mudflow hazard used by the specialists of the Institute of Geography and Water Security are based on the criteria for the outburst hazard of glacial lakes.

According to the degree of mudflow hazard, glacial lakes are divided into the following categories: non-outburst hazardous, potentially outburst hazardous, outburst hazardous, very outburst hazardous.

Qualitative criteria for the degree of outburst hazard of glacial lakes include lake types, types of a hydrological regime, conditions of discharge of the lake basins, structure of the lake dams [5, 7]. Lakes can belong to the following types: thermokarst, periglacial-depressive, and cirque ones. According to the type of hydrological regime, lakes are divided into stationary, periodically filling, and non-stationary. Conditions of discharge of the lake basins are divided into the following ones: underground runoff, surface runoff, and filtration runoff. Among the types of lake dams’ structures, the following ones are distinguished: moraine with multiple voids, monolithic of frozen detrital rocks with lenses of buried ice, monolithic with a complete absence of buried ice, frozen layers and voids.

Quantitative criteria are the size of glacial lakes: the area of the lake's water surface and the volume of the lake [5, 8]. By the area of the water surface, lakes are divided into 5 categories: 1) < 5, 2) 5-10, 3) 10-50, 4) 50, 5) >100 thousand m^2. By the volume of water, lakes are divided into 3 categories: 1) $n \cdot 10$; 2) $n \cdot 100$; 3) $n \cdot 100$; 4 - $n \cdot 1000$ thousand m^3.

Potentially outburst hazardous are the lakes with a volume of more than 50 thousand m^3, slowly filling up in the last 10 years (n * 10 thousand m^3).

The lakes with a volume of more than 50 thousand m^3, which have increased their volume by 100 thousand m^3 in the last 10 years, are considered to be outburst hazardous. The lake dam of such lakes contains large massifs of buried ice.

The criteria for identifying very outburst hazardous lakes include the possibility of severe consequences if they outburst. These include the presence of a mudflow risk area with a population of over 50 people and the absence of engineering mudflow protection structures.

Formalized methods of background medium-term and short-term forecasts of glacial mudflows are used to assess the mudflow hazard. The predictors of the medium-term forecast are the data from the Mynzhylky meteorological station (MS) in the upper reaches of the Kishi Almaty River: average daily air temperature and the sum of these temperatures from 01.05 of the current year, exceeding 108 % of the average long-term value; precipitation amounts for 10 and 30 preceding days (30 and 95 mm, respectively), the height of the zero isotherm at 06 a. m. and its average value for 10 and 30 days.

The critical conditions for the formation of glacial mudflows in the short-term forecast are the following values of hydrometeorological factors: the sum of the average daily air temperature from May 1 to the forecast date at the Mynzhylky MS is not less than 108 % of its average long-term value; the critical values of the height of the zero isotherm for 10 and 30 days (4 200 and 4 000 m); the average height of the zero isotherm for ten days before the forecast date is not lower than 4

200 m, and not lower than 4 000 m for 30 days; the sum of precipitation at the Mynzhylky MS for ten days before the forecast date is ≥ 30 mm, and ≥ 95 mm for 30 days.

In the event of the appearance of a new lake (filling of a previously empty basin), a forecast of " possible mudflows " is made regardless of meteorological conditions.

The Institute of Geography and Water Security has developed a method for quantitatively assessing the risk of glacial lake outbursts based on the relationship between their areas and volumes. The results of the certification of lakes in Ile Alatau, conducted by Kazakhstan Mudflow Protection Service in the 1980s, which included tacheometric and bathymetric measurements of lake basins, made it possible to establish this relationship in the form of a formula [8] (Fig. 1):

$$x = 0{,}059\, y^{1.44} \quad (1),$$

where x is the volume of the lake (m^3) and
y is the area of the lake's water surface (m^2).

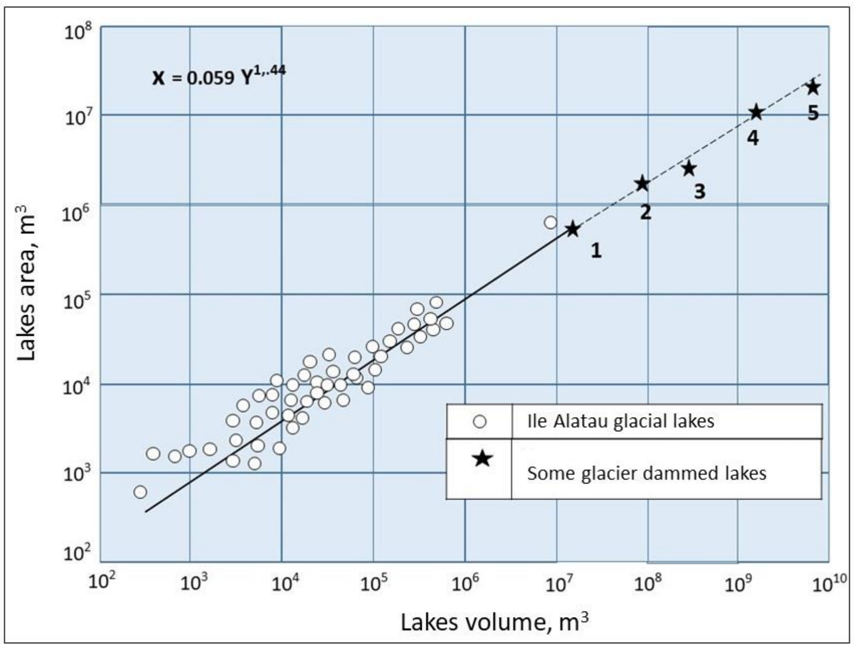

Figure 1. The relationship between the volumes and areas of the glacial lakes of Ile Alatau according to the data of the lakes' certification performed by Kazakhstan Mudflow Protection Service

Later, in 2017, the Institute of Geography conducted an inventory of glacial lakes in Ile and Zhetysu Alatau using *Sentinel 2* satellite images. The lake images were digitized using the *ArcGis* program. The volumes of the lakes were determined according to the empirical relationship between the areas of the water surface and the volumes of the lakes, identified for 45 water reservoirs in Ile and Zhetysu Alatau. This relationship is approximated by the equation:

$$y = 0{,}044x^{1.476} \quad (2),$$

where y is the volume of the lake (m^3) and
x is the area of the water surface of the lake (m^2).

A comparative calculation using formulas (1) and (2) for glacial lakes with similar area values showed that the difference in determining volumes is no more than 4 %, which means that both formulas can be used. The calculations performed make it possible to significantly simplify the process of collecting actual data on the volumes of glacial lakes using remote sensing data on their areas.

The determining criterion for assessing the risk of glacial lake outbursts is the peak outburst discharges, which are the main factor for the formation of glacial mudflows. It is possible to calculate the values of peak water discharges during lake outbursts based on the volume and time of water outflow from the lake basin. However, in most cases, it is not possible to apply this method, since glacial lake outbursts are quite rare natural phenomena, so it is impossible to record the exact time of water outflow from the lakes due to the lack of direct observations of the process. It was possible to obtain the values of peak discharges during glacial lake outbursts when recording a drop in the water level in the lake basin during the outburst and the time of water outflow only in a few cases.

The data from direct observations of lake basin emptying and ground surveys conducted after the events of outburst glacial mudflows make it possible to identify the following mechanisms of glacial lake outbursts:

- surface flow through open ice channels in lake dams,
- underground flow through ice tunnels, and
- surface flow through channels in melted massifs of modern moraines.

The observation results showed that the peak water discharges through an open ice channel can be calculated using the formula:

$$Q_{max} = \lambda F \quad (3),$$

where Q_{max} is the peak water flow (m^3/s),
λ is intensity of deepening of an open ice channel (m/s), and
F is the area of the lake (m^2).

For the Ile Alatau conditions, the maximum values of λ were very close and averaged 0.00017 m/s or 0.612 m/hour. In the Caucasus, when overflowing through the ice dam of the lake, the same intensity of deepening of the open channel due to heat exchange was noted (0.6 m/hour) [4].

Tunnel outbursts of glacial lakes are known for many mountainous regions. Empirical formulas for calculating the peak flow rates during outbursts of glacial lakes through tunnels for different regions of the world are given in Table 1).

Table 1. Empirical formulas for calculating the peak discharges during glacial lake underground outburst through ice tunnels, obtained for various mountainous regions

Lake Dam Type	Calculation Formula		References
Moraine with Buried Ice Core	$Q_{max} = 75\ (V/10^6)^{0,67}$	(4)*	[9]
	$Q_{max} = aW^{5/4}\sqrt{H}$	(5) *	[2]
	$Q_{max} = 0,0000055\ (P_E)^{0,59}$	(6)**	[10]
	$Q_{max} = 46\ (V/10^6)^{0,66}$	(7)	[14]
	$Q_{max} = aW^{1,25}H^{0,5}$	(8) ***	[6]

where α is an empirical coefficient depending on the tunnel length,
W is the cross-sectional area of the tunnel (m^2),
H is the excess over the tunnel entrance (m).
Notes: * the maximum discharge during the initial period of flow into the tunnel for lakes dammed by a glacier;

** P_E is the potential energy of the reservoir, determined as a result of the height of the lake dam (m), volume (m^3), and specific gravity of water (9 800 N/m^3);
*** formula (8) specifies formula (3) by introducing the numerical value of the coefficient ($\alpha = 2.7$) for the Ile Alatau lakes.

Lake outbursts caused by dam destructions are well known for many regions. Empirical formulas for calculating the peak outburst discharges in the event of dam failures are given in Table 2.

Table 2. Empirical formulas for calculating lake outbursts with destruction of lake dams based on data from different regions

Causes of Lake Outbursts	Formula		References
Surface Outburst along the Channel in the Thawed Massif of Modern Moraines	$Q_{max} = 0,0048\ V^{0,896}$	(9)	[13]
	$Q_{max} = 0,00013\ (P_E)^{0,60}$	(10)	[10]
When a Glacier Collapses into a Lake	$Q_{max} = V/t_w$	(11)	[12]
	$Q_{max} = 1100(V/10^6)^{0,44}$	(12)	[14]
When a Rock Fall Occurs	$Q_{max} = 0,72V^{0,53}$	(13)	[11]

An adequate assessment of the relationship between the outburst discharges of glacial lakes and the mudflows formed by them was carried out only for those cases where the characteristics of outburst floods were determined, and the maximum discharges of glacial mudflows were measured instrumentally in sections immediately below the mudflow centers. The data on these events in Ile and Zhetysu Alatau are given below.

The maximum discharges of turbulent mudflows at the outlet of the mudflow centers were determined using the “velocity – area” method applying the formula obtained for Ile Alatau [14]:

$$v = 4,25 \cdot h_{cp.}^{0,5} \cdot i^{0,17} \quad (4),$$

where v is the mudflow velocity (m/s),
h_{cp} is the average mudflow depth (m), and
i is the slope (%).

For the Ile Alatau conditions, refined regional formulas for calculating outburst floods of glacial lakes were obtained:

- for surface outbursts along open ice channels $Q_{max} = \lambda F$,
- for underground outbursts through ice tunnels $Q_{max} = 75\ (V/10^6)^{0.67}$,
- for surface outbursts along channels in thawed massifs of modern moraines $Q_{max} = 0.0048\ V0^{.896}$.

A correlation relationship between the peak outburst discharges and the maximum discharges of glacial mudflows at the exit from mudflow centers was established. It is determined by the following formula:

$$Q_{mudflow} = 18,925 \cdot Q_{flood},$$

where $Q_{mudflow}$ is the maximum flow rate of the mudflow at the outlet from the mudflow center (m^3/s) and
Q_{flood} is the maximum flow rate of the outburst flood, m^3/s.

The Institute of Geography and Water Security developed a methodology for calculating mudflow risk. The methodology includes mudflow risk in general, its economic, social and environmental components. Risk (damage/time) is determined by the frequency of events (event/time) per average damage (damage/event).

For the economic component of mudflow risk $\mathbf{R_i^E} = \sum \overline{\mathbf{p_i}} \times \mathbf{EV_i}$ (objective); $\mathbf{R_B^E} = \sum \mathbf{R_i^E}$ (basin), where EVi is the economic cost of restoring the i-th object; $\overline{\mathbf{p_i}}$ is the probability of mudflow impact on the i-th object.

For the social component of risk Rmf = Pmf · Vs · Vt · d · Kl · F (collective risk), where Rmf is the collective mudflow risk; Pmf is mudflow recurrence; Vs is the population vulnerability in space; Vt is the population vulnerability in time; d is the population density; Kl is fatality rate; and F is the populated area.

For the environmental component of mudflow risk $\mathbf{R_{Eg}} = \overline{\mathbf{p}} \times \mathbf{NW_{TW}} \frac{\mathbf{S_{TW}}}{\mathbf{S_{MW}}}$; $\overline{\mathbf{p}} = \frac{\sum \overline{\mathbf{p_i}} \times \mathbf{EV_i}}{\sum \mathbf{EV_i}}$, where $\mathbf{R_{Eg}}$ is the environmental component; NW_{TW} is the cost estimate of the natural wealth of the river basin; S_{MW} is the area of the territory prone to mudflows; and S_{TW} is the area of the study territory.

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