# Synthesis report on GLOF hazard and risk in Kazakhstan

## *State of Knowledge*

# Outline

# 1. Introduction

Central Asia is facing important challenges in view of coping with adverse effects of climate change. Like many other mountain regions worldwide, Central Asia is particularly sensitive to changes in global climate, from both a physical and societal perspective. The retreat and disappearance of mountain glaciers and thawing of permafrost are clear indicators of warming in a rapidly changing glacial and periglacial environments. As a direct consequence, the size and number of glacial lakes are increasing, and so too is the risk of Glacial Lake Outburst Floods (GLOFs), and glacial mudflows.

GLOFs refer to the sudden discharge of a water reservoir that has formed either underneath, at the side, in front, within, or on the surface of a glacier, and related dam structures can be composed of a mix of ice, moraine or bedrock. Some glacial lakes gradually enlarge over time at the front of the glacier, while other, non-stationary lakes can be more erratic, fluctuating in size over short time scales. The potentially high discharges and sediment content of GLOFs can devastate local lives and livelihoods. This is particularly true in rural, mountain communities, where socio-economically disadvantaged, indigenous groups, ethnic minorities, women, children, and elderly are highly sensitive and particularly vulnerable to the impacts of climate change. However, the societal impacts of GLOFs can be far-reaching (>100 km) as a result of direct impacts or chain reactions, such as damming of valleys, secondary outbursts and mudflows. As such, approaches to GLOF hazard and risk assessment must consider large spatial scales, often in a transboundary regional context.

Recognising this significant and increasing threat to the region, the UNESCO-led project "Reducing vulnerabilities of populations in the Central Asia region from glacier lake outburst floods in a changing climate" (GLOFCA), was initiated in 2021 under the Adaptation Fund. A key outcome of the GLOFCA project will be the establishment of four demonstrative GLOF Early Warning Systems (EWS) in selected pilot sites within Kazakhstan, Kyrgyzstan, Tajikistan, and Uzbekistan. In order to provide a robust scientific basis for the design and implementation of these Early Warning Systems, a comprehensive synthesis of the state of knowledge on GLOF hazard and risk is being undertaken for each country. As a series of 4 reports, each synthesis draws on the wealth of scientific information and data that has been gathered over many decades by national authorities and research institutions, complimented with international studies and perspectives.

The four national synthesis reports follow a common format. First, a synthesis of cryospheric change in the region is provided. This is followed by a comprehensive review of reported GLOF and mudflow disasters. Methodological approaches to lake mapping and monitoring are then outlined, and then finally, the methods, criteria, and classification schemes used to assess hazard and risk are presented.

## 2. Cryospheric change across Kazakhstan.

The cryosphere is a great indicator of atmospheric and environmental changes, as climate fluctuations translate in changes in essential climate variables, i.e. glaciers, permafrost and snowcover. Glaciers are also a valuable water resource, especially important for arid territories as glaciers collect solid precipitation during winter and release it as meltwater in summer providing a reliable water supply in dry years. Climate change and concomitant glacier recession has caused the development and expansion of glacial lakes in mountain areas of the world, which leads to an increasing risk of lake outbursts. Outbursts of glacial lakes represent a serious hazard especially for populated regions in the mountains all over the world (Bolch et al., 2011). Central Asia is at the boundary between temperate and subtropical climate zones. It is characterized by an extremely continental climate and by having regional differences in seasonal and annual precipitation due to strong topographical effects. Western and north western plains of central Asia are influenced by moist air masses from the Western Atlantic region; whereas in the south and east of Central Asia mountain ranges make a barrier effect that almost completely isolate the region from moist air masses from the Indian Ocean, thus arid and cold conditions dominate in the eastern part of Tien Shan and Pamir (Barandun et al., 2020). The summer ablation and the possible combined effects of global warming and atmospheric circulation changes over the north Atlantic and north Pacific has led to a glacier mass loss of 270 ± 140 Gt and glacier area losses of 2960 ± 1030 km$^2$ in Tian Shan Mountains, Central Asia during 1961–2012, and this rate is almost four times the global average (Farinotti et al., 2015). The most dramatic glacial shrinkage has been observed in the outer and low-altitude ranges of the Tian Shan Mountains, which are densely populated and snow and glacial melts are particularly important for regional water resources (Sorg et al., 2012). The two main glacierized mountain regions in Kazakhstan are the Zhetysu Alatau and the Ile Alatau in the Tien Shan Mountain Range. These regions hold all the studies collected in this report.

Kazakhstan is characterized by 4 main types of water regime of rivers (Plekhanov et al., 2019): the Kazakhstan (N/NW and center: steppe and semi-desert); the desert (arid central and W parts) and the two mountainous regimes: The Tien Shan type in SE and S Kazakhstan, whose sources are in the zone of snow and glaciers; and the Altai type characteristic of the rivers of the mountainous regions of E Kazakhstan, in the middle mountain zone.

Due to the topography, the overall continental climate is characterized by distinct local variability. Precipitation at altitudes about 3,000 m a.s.l. ranges from more than 1,000 mm/a on windward northern slopes to less than 800 mm in a leeward valley south of the main mountain ridges (Bolch, 2007). The minimum precipitation occurs in the study area during winter due to the Siberian anticyclone and the maximum occurs in early summer due to both cyclonic activity and convective precipitation (Böhner 1996). Mean annual air temperature (MAAT) recorded at Tuyuksu glacier station (3,434 m a.s.l.) is about -4$^0$C. The zero degree isotherm is situated just above 2,700 m a.s.l.. The steady-state equilibrium line altitude of glaciers is situated at about 3,800 m a.s.l. on northern slopes and between 3,900 and 4,000 m a.s.l. on southern slopes (Bolch 2007). A characteristic feature of the northern Tien Shan is its pronounced periglacial zone with many large and active rock glaciers. This zone is characterized by frequent diurnal freeze–thaw cycles (Marchenko 1999). Permafrost is sporadic at about 2,700–3,200 m a.s.l., discontinuous at 3,200–3,500 m a.s.l., and continuous above 3,500 m a.s.l. (Gorbunov et al. 1996).

Increasing air temperatures and heterogeneously changing precipitation rates have led to diverging effects on the seasonal snow cover in the Tien Shan region (Sorg et al., 2012). For the total Tien Shan, maximum snow cover thickness has decreased by approximately 0.1 m and snow cover duration by 9 days, respectively, between 1940 and 1991 (Sorg et al., 2012). Sorg et al., 2012 report a decrease in maximum snow cover thickness and snow cover duration at all altitudes in western and central Tien Shan but no trend in the northern Tien Shan for altitudes above 2000 m a.s.l. (Barandun et al., 2020) report an increase in snow depth for central Tien Shan. They attribute this to an increase in winter precipitation.

In the Tien Shan, permafrost temperature has experienced a continuous warming since the 1950s leading to a thickness increase of the average active layer by 23% compared to the early 1970s (Marchenko et al., 2007). According to the results of model estimations, the lower boundary of permafrost distribution has shifted upward by about 150-200 m during the 20$^{th}$ century, and the area of permafrost distribution in two river catchments in the northern Tien Shan has decreased by approximately 18% (Marchenko et al., 2007)

The Zhetysu Alatau is located at the NE flank of the Tien Shan. The climate is characterized by strong seasonal contrasts in temperature and precipitation. In winter, the region is dominated by the western extension of the Siberian anticyclone (low temperatures and precipitation). In autumn and spring the westerly flow dominates, with frequent depressions and precipitation maxima in October–November and April–May. In summer, the thermal Asiatic depression dominates and the advection of warm, dry air from the south results in low precipitation. The accumulation period extends between mid-September and early June; the ablation period is limited to June–July–August (Kapitsa et al., 2017). The maximum elevation is 4622m a.s.l. but most peaks extend to about 3800 m a.s.l. The glacier snouts descend to approximately 3400m a.s.l. In 1956, the glacierized area was 814 km$^2$, and reduced to 465 km$^2$ in 2011 (Vilesov et al., 2013). By 2011, 103 glaciers (half of those catalogued in 1956) had disappeared (Vassiliy Kapitsa et al., 2017). At present, the northern sector (basins of the Bien, Aksu and Lepsy rivers) is most heavily glacierized, followed by the southern (basins of the Khorgos and Usek) and then western (the Karatal basin) sectors. The number and combined area of glaciers decline towards the east (basins of the Tentek, Tastau and Rgaity) (Kapitsa et al., 2017). The Zhetysu Alatau is one of the mountain regions of Central Asia where lakes are particularly widespread and where glacier retreat rates are among the highest in the region (Severskiy et al., 2016). Between 1955 and 2011, 48% of the glacier area was lost; between 2000 and 2011, glaciers lost 12% of their combined area, retreating at a rate of 1.1% per year (Kapitsa et al., 2017). Vilesov et al. (2013) reported a widespread degradation of permafrost and melt of buried ice across the region.

As for the Ile Alatau Mountain Region, (Narama et al., 2009) analyze glacier area changes from 1970 to 2007 using satellite data (Corona for 1970; Landsat for 2000; ALOS for 2007) and found that in 30 years (1970-2000) glacier area decreased 12% in the region and by 4% over the last 7 years of their study (2000-2007) due to rising summer temperatures. The maximum precipitation in this region occurs when the weakened Siberian High allows moisture to arrive from the west in spring and from the north in summer. Accumulation occurs during spring/summer, meaning that the seasons of highest accumulation and ablation are close or even coeval. This is characteristic for the "summer-accumulation glacier type" in the Himalayas (Ageta and Higuchi, 1984), in which air temperature strongly controls both snow fall and melting. Ile-Kungöy region has many large glaciers (>5 km$^2$) and thus, it has not shown a large percentage of glacier reduction. It´s glacier cover was ~672 km$^2$ in 1970 and in 2007 564 km$^2$. Glacier shrinkage is expected to have two main impacts on populated areas of the region, such as the city of Almaty: water shortage in summer and increase threat from glacier hazards such as GLOFs.

## 3. Past GLOF and glacial mudflow disasters in Kazakhstan.

30% of the territory of Kazakhstan is affected by mudflows, in particular the mountain regions of Altai, Zhetysu Alatau and Tien Shan (Medeu, 2015). In this report we focus on the Ile Alatau and Zhetysu Alatau regions, where scientific literature has put its spotlight. A note on nomenclature: Ile Alatau was formerly called Zailiyski Alatau or Trans-Ili Alatau; Zhetysu Alatau was formerly called Djungarskiy or Dzungarskiy Alatau. For clarity, in this document we will use the terms Ile Alatau and Zhetysu Alatau.

Ile Alatau is one of the most mudflow hazardous mountain regions in Kazakhstan and at the same time the area is distinguished by high socio-economic development (Medeu et al., 2020). The large city agglomeration of Almaty with a population of more than 2.5 M people is situated o then mudflow cones of the northern slope of the y Alatau range. Mudflow disasters with numerous casualties and great material damage occurred in 1956, 1963, 1973, 1977, 1979, 1980 and 2015 (Esenov U. E., Degovets A. S., 1979; Medeu et al., 2019; Popov N.V., 1984; Shusharin V. I., Popov N. V., 1981).

The Zhetysu Alatau is one of the mountain regions of Central Asia where lakes are particularly widespread and where glacier retreat rates are among the highest in the region (Severskiy et al., 2016). A number of GLOF and mudflows events were reported in the region in the 1970s and early 1980s. The largest recorded mudflow in the region took place in 1982 when a cascade of lake outbursts (Lake Akkol into Lake Tranzitnoe then into Lake Kokkol) with an estimated volume of water and transported material of approximately 2.7 M m3 reached the town of Sarkand, 45 km downstream, which suffered from widespread destruction of infrastructure (Kapitsa et al., 2017). Other disastrous GLOF-originated mudflows occurred in 1963 (Esik, 5,8M $m^3$), 1973 (Kishi Almaty, 4M $m^3$), 1980 (Kaskelen, 2M $m^3$), 1970 and 1978 (Aksu), 1979, 1993 and 2014 (Sredniy Talgar) (Blagovechshenskiy et al., 2015) in the Ile and in the Zhetysu Alatau region.

- **What are the process types?**

The hazardous processes generally encountered in the Kazakhstan Mountains are debris flows/mudflows, both rain-induced and from glacial origin. The causes for formation of glacial mudflows are outbursts of subglacial reservoirs or moraine lakes, as well as collapses of moraine slopes. Glacial Lake Outburst Floods (GLOFs) are a catastrophic release of water reservoir formed either at the side, in front, within, underneath or on the surface of a glacier. Dam structures that contain the water reservoir can be composed primarily of glacial ice, morainic debris or bedrock (GAPHAZ, 2017).

A characteristic feature of the northern Tien Shan is its pronounced periglacial zone with many large and active rock glaciers (Bolch et al., 2011). Lake dams are predominantly composed of morainic material, and thawing of permafrost and buried ice increases the risk of moraine failure and lake outburst (Popov, 1986; Jansky et al., 2010; Bolch et al., 2011). From historical analysis of debris flows, (Medeu et al., 2019) report that rainfall-induced debris flows are usually formed when daily precipitation exceeds 40 mm. For the debris flow to be catastrophic the precipitation exceeds 70 mm. As for glacial debris flows, in some cases they are a result of a chain of subsequent processes. For example, the GLOF on July 7th 1963 in the basin of the Esik River (Ile Alatau) arose as a result of sub-glacial lake outburst near the Zharsai glacier, which led to a subsequent process cascade and the outburst of the Esik Lake, dammed by an ancient landslide. The initial volume of the glacial lake outburst was 460,000 $m^3$, but as a result of intense entrainment processes, the maximum mudflow discharge was estimated at 7,000 - 12,000 $m^3$/s with a total volume of 5.8 million $m^3$. This event led to catastrophic consequences with numerous human casualties (Popov N. V., 1981; Zems A. E., 1976). After this event, mitigation measures started to be put in place for protection of the Almaty river basin and its population of over 2,5 M (Medeu et al., 2019).

A subglacial lake can form when an ice channel gets blocked. It can grow and drain, through the opening of an ice tunnel, extremely quickly over the period of just a few months (Narama et al., 2018). The blockage and opening process of ice tunnels can lead to repetitive growth-drain cycles of subglacial lakes. These lakes typically start forming in May, expand throughout the summer filled by ice and snow melt, and drain around the end of July and mid-August when ice tunnels reopen due to ice melting (C.

Narama et al., 2018). Moraine-dammed lakes are considered dangerous (Janský et al., 2009) and the drainage is often caused by a failure of the moraine dam (Narama et al., 2018). Ice-dammed lakes release water along lateral moraines or through the glacier itself. Ice channels can be closed due to ice deformation and lakes can fill up until they create another outlet creating a GLOF. (Mayer et al., 2008).

The susceptibility of a dam to failure mainly depends on the characteristics of the lake dam itself. In Kazakhstan, most of the lake dams are made of morainic materials with a buried ice core and in permafrost conditions. The width and height of the dam as well as the freeboard between the lake level and the crest can be visually determined by means of a high resolution DEM and satellite imagery (Bolch et al., 2011). The possibility of a lake's outburst mainly depends on the dam's stability. The lakes dammed by young moraines with an ice core show the highest possibility of outburst. Proglacial lakes are mostly often among them (Blagovechshenskiy et al., 2015).

- **Known triggering and preconditioning factors.**

The triggering and preconditioning factors of lake drainage depend on the type of lake and dam, the nature of underground tunnels, the condition of dead ice in moraines, glacial water infiltration etc. (Daiyrov et al., 2019). Since 1900, 481 debris flows with volumes of more than 1000 $m^3$ have been recorded in Ile Alatau. Of them, 364 (76%) debris flows were caused by rainfall, and 117 (24%) were glacial debris flows (A. R. Medeu et al., 2019).

(Medeu et al., 2019) consider that in the Ile Alatau region, debris flows are most frequently caused by heavy rains (rainfall-induced debris flows) and outbursts of glacial lakes (GLOFs). Rainfall induced debris flows are usually formed when the daily precipitation amount exceeds 40 mm. Catastrophic debris flows occur if the precipitation amount exceeds 70 mm. Glacial debris flows are observed in the period of maximum glacier melting, when maximum daily air temperatures in the glacial zone exceed 15$^{o}$C. The overall yearly distribution of debris flows shows two maxima: the first maximum in the second ten-day period of June which are rainfall-induced, and the second maximum in the second ten-day period of July which are glacial debris flows.

(Kapitsa et al., 2017) report that GLOF events peaked in the Zhetysu and Ile Alatau between 1975 and 1984 when strong positive JJA temperature anomalies and enhanced glacier melt were observed. Two GLOF events occurred in 2014 and 2015 in the Ile Alatau following strongly positive JJA temperature anomalies of 2–3ºC (reaching 6ºC in July 2015) recorded at the Tuyuksu meteorological station (3440m a.s.l.).

In July 23$^{rd}$ 2015 a mudflow hit Kazakhstan's largest city of Almaty. The GLOF came from the outburst of morainic lake Bezymyannoye at Kargaly glacier that held 40,000 $m^3$ of water releasing part of the water downhill. This triggered a series of mudflows, with part of them overtopping the dam on the Kargaly River. According to the Emergency Situations Committee of Kazakhstan's Internal Affairs Ministry, the mudflow was triggered by the excessively hot weather in the area, which made the glacier melt faster and overfill the Bezymyannoe Lake, after which a large mass of water along with debris flowed down the Kargalinka river. The Committee informed that more than 18,000 $m^3$ of mud had been removed from the area. Two days later, a danger of another mudflow emerged at the opposite edge of the city along the Talgar River due to heavy rains high in the mountains and intense melting that increased the water flow rate in the river to 27 cubic meters per second (https://reliefweb.int/report/kazakhstan/mudflow-consequences-being-remedied-almaty-danger-persists).

See table in Annex on historical debris flows in Ili Alatau from 1900 until 2015 taken from (Medeu et al., 2019).

- **Triggering factors according to state institution Kazselezashchita.**

The main reasons for the breakthrough of high-mountain lakes, according to the state institution "Kazselezashchita", are:

1. Destruction of lake barriers because of thawing of soils of the surface runoff channel with the formation of a destructive water flow. During the period of intense ablation of glaciers in July-August, lake basins are filled with water to maximum levels, and the risk of outburst danger increases with the formation of a mudflow. When stationary lakes break through, usually along surface runoff channels, in the zone of formation of thawed massifs, significant destruction of dams occurs, and powerful glacial mudflows are formed.
2. Emptying the lake through intra-morainic runoff channels through funnels, intra-morainic grottoes (ice tunnels), with the release of water flows to the surface, which previously provided household melt runoff from the lake.
   Due to the long-term impact of lake waters on basins composed of buried glacial ice and permafrost, stationary reservoirs are intensively developing. This is confirmed by repeated bathymetric surveys of most of the lakes.

The conditions for the development, existence, and filling regime (accumulation and drawdown) of non-stationary lakes differ from those for stationary lakes. Non-stationary lakes are distinguished by the following characteristic features:

• lakes are filled at the very beginning of the ablation period and there were cases of their filling in the pre-winter period;
• in winter and at the beginning of spring there is no water in the lake basin or there is an insignificant amount of water. Water levels in lakes are affected by the inflow of water from glaciers and the carrying capacity of intramoraine runoff channels.
• The filling of lakes occurs as a result of the blocking of ice tunnels (intra-moraine runoff channels), through which melt water is usually discharged;
• lake basins may not be filled for a number of years;
• at maximum filling, these lakes can exist from several days to several years, followed by a breakthrough;
• lake dams have an ice core covered by a moraine cover;

Breakthroughs of non-stationary lakes occur as a result of the opening of underground runoff channels. It is also possible to empty such lakes during the surface overflow, due to the formation of an open ice channel in the body of the dam.

The number of non-stationary lakes is much less than stationary ones, but they account for more than half of all catastrophic glacial mudflows that have formed in Ile Alatau in recent years.

Developing lake basins are characterized by an intensive increase in water volumes over a short period (1-10 years). During this period, an increase in the lake water area and the basin of the lake is observed. The intensive development of lake basins leads not only to the rapid accumulation of large volumes of melt water in them, but also increases their breakthrough danger. A particularly dangerous period of developing lakes is the first year or three years. After a period of 20 years or more, the lakes can go into the stage of degradation (aging), the breakthrough danger is reduced to a minimum, and the processes of sedimentation of the surface of the lake basin occur.

- **Where have the events occurred** AND **Impacts on society in terms of losses and fatalities.**

“Mudflows in the territory of the USSR and measures to combat them. Index of literature published in 1968-1991”. (Ними, 2008) (IN RUSSIAN) by Professor V.F Perov which includes an index of literature published between 1968 and 1991.

(Medeu et al., 2019) and (Medeu et al., 2020) (IN RUSSIAN) provide a review of the debris flow activity in the Ile Alatau region from 1900 to 2019 (Table 1), based on material from scientific publications and archival data of RSE Kazhydromet (Ministry of Ecology, Geology and Natural resources of the RK) and the Anti-Debris Flow Service. Since 1900, 481 debris flows with volumes of more than 1000 $m^3$ have been recorded in Ile Alatau. Of them, 364 (76%) debris flows were caused by rainfall, and 117 (24%) were glacial debris flows. The total number of very large debris flows was 9 (2%), and the number of large, moderate and small debris flows was 24 (5%), 92 (19%) and 356 (74%), respectively. Debris flows of more than 10 thou $m^3$, which can do a significant damage, make up 26% of all debris flows. Only nine debris flows (less than 2%) were very large debris flows but they accounted for most of the damage and for most of human losses. From these nine very large events, seven of them were glacial debris flows. In the Anexe a table is included collecting information on historical debris flows in Ile Alatau from 1900 until 2015 taken from (Medeu et al., 2019). The largest mudflows occurred in 1977 (6 M $m^3$), 1963 (5.8 M $m^3$), 1958 (4 M $m^3$), and 1973 (3.8 M $m^3$). The causes for formation of glacial mudflows were outbursts of moraine lakes or subglacial reservoirs, as well as collapses of moraine slopes. Since 1951, occurrence of glacial mudflows increased and reached its maximum in the 1970s. Since 1978, the number of glacial mudflows decreased, although their volumes remained large until the late 1990s. From 1997 to 2013, mudflow activity was low and with volumes below 10 thousand $m^3$. Since 2014, there has been an increasing tendency in mudflow activity.

**Table 1** taken from (A. P. Medeu et al., 2020): The largest glacial mudflows from 1950 in Ile Alatau. Columns are: date; river basin; mudflow center; water volume in lake (thousand $m^3$); discharge/transported volume sat down (M $m^3$); maximum flow rate ($m^3$/s); damage.

*Таблица 1.* **Наиболее крупные гляциальные сели**

| Дата | Бассейн реки | Селевой очаг | Объём воды в озере, тыс. $м^3$ | Объём селя, млн $м^3$ | Максимальный расход селя, $м^3$/с | Ущерб |
|---|---|---|---|---|---|---|
| 20.08.1951 г. | Киши Алматы | Морена ледника Туйыксу | 20 | 0,2 | Нет данных | Разрушены мосты |
| 07.08.1956 г. | | | 32 | 1,1 | 1000 | Большие разрушения, человеческие жертвы |
| 06.07.1958 г. | Есик | Озеро под ледником Жарсай | 250 | 4,0 | Нет данных | Уничтожен еловый лес в долине р. Есик |
| 07.07.1963 г. | | | 450 | 5,8 | 12 000 | Уничтожено оз. Есик, большие разрушения, человеческие жертвы |
| 15.07.1973 г. | Киши Алматы | Озеро под ледником Туйыксу | 230 | 3,8 | 10 000 | Большие разрушения, человеческие жертвы |
| 19.08.1975 г. | Улкен Алматы | Морена под ледником Молодёжный | 5 | 0,1 | 300 | Разрушены мосты и дорога |
| 03.08.1977 г. | | Озеро под ледником Советов | 88 | 6,0 | 11 000 | Большие разрушения, человеческие жертвы |
| 03.07.1977 г. | Есик | Озеро под ледником Жарсай | 430 | 0,4 | 630 | Отсутствует |
| 21.06.1979 г. | Средний Талгар | Озеро под ледником Спортивный | 82 | 0,3 | 340 | Уничтожен альпинистский лагерь |
| 23.07.1980 г. | Каскелен | Озеро № 16 | 290 | 2,0 | 500 | Разрушены мосты, дорога |
| 30.06.1982 г. | Есик | Морена ледника Жарсай | Нет данных | 1,0 | Нет данных | Отсутствует |
| 07.08.1982 г. | | | | 0,5 | | Разрушены мосты |
| 06.07.1993 г. | Средний Талгар | Озеро под ледником Безымянный | 100 | 2,0 | 2000 | Разрушены мосты, дорога, дома, ЛЭП |
| 03.07.1994 г. | Улкен Алматы | Озеро под ледником Аршалы | Нет данных | 0,1 | 500 | Отсутствует |
| 17.07.2014 г. | Средний Талгар, | Озеро под ледником Солнечный | 50 | 0,3 | 300 | Разрушены мосты, дорога, дома, ЛЭП |
| 23.07.2015 г. | Каргалы | Озеро под ледником Каргалинский | 80 | 0,15 | 40 | Подтоплены жилые дома |

(for table in English see Table A1 in Annex)

Another comprehensive publication on glacial debris flow processes on the Northern slope of Ile Alatau in the 20th century is provided by (Yafyazova, 2011). In this publication, a detailed description of the events presented in Table1 from (Medeu et al., 2020) is provided.

(Kapitsa et al., 2017) look into mountain lakes and lake outbursts in the Zhetysu Alatau region. A number of GLOF events, followed by mudflows, were reported in the Zhetysu Alatau in the 1970s and early 1980s, when positive temperature anomalies were close to those observed in the 2010s, e.g. in the upper reaches of the Aksu River in 1970 and 1978 and the Sarkand valley in 1982 (Medeuov et al., 1993). In 1982, the outburst of Lake Akkol in the upper reaches of the Sarkand River at about 3200m a.s.l. followed by a chain of lake outbursts – the discharge into Lake Tranzitnoe and then Lake Kokkol which were both overtopped - led to the formation of the largest recorded mudflow in the region, with an estimated volume of water and transported material of approximately 2.7 M $m^3$ . The maximum discharge was estimated as $2300m^3/s$ . Within the town of Sarkand, located 45 km downstream, discharge reached $300m^3/s$, leading to a widespread destruction of infrastructure (Tikhomirov and Shevyrtalov, 1985).

## 4. Lake mapping and monitoring

Climate change and glacier recession has caused the development and expansion of glacial lakes in mountain areas of the world leading to an increasing risk of lake outbursts which represent a serious hazard especially for populated regions in the mountains all over the world (Bolch et al., 2011).

(Vassiliy Kapitsa et al., 2017) provide a literature review of lake mapping, inventorying and monitoring. They mention works such as: (a) Wang et al. (2013) compiled an inventory of lakes with individual areas of more than $2000m^2$ for the Tien Shan, reporting an increase in the count and combined area of lakes of 22.5% and 16.7- 2.9% respectively between 1990 and 2010. (b) Wang et al. (2015) assessed water storage in lakes of the Tarim Basin (China, S Tien Shan), reporting a decline in the levels of glacier-fed lakes, despite the observed glacier thinning and negative mass balance, and they attributed this discrepancy to water abstraction for agricultural needs. (c) Bolch et al. (2011) assessed the hazard potential of 132 lakes in the Ile Alatau. (d) Other studies, including Narama et al. (2010), Jansky et al. (2010), Medeu et al. (2013) and Herget et al. (2013), and earlier studies from the 1970s to the 1990s reviewed by Medeuov et al. (1993) and more recently by Evans and Delaney (2015) focused on hazard potential of individual lakes, particularly in the densely populated Ile Alatau. (e) An inventory for the year 2002 using Landsat imagery was compiled by Severskiy et al. (2013) for selected regions in the Zhetysu Alatau reporting that the majority of lakes were located between 3300 and 3600m a.s.l. on either young (20th or 21st century) or LIA and older moraines. (f) Medeu et al. (2013) examined changes in 48 lakes in the catchment of the river Khorgos (transborder Zazakhstan-China) between 1978 and 2011 using the USSR 1 : 100 000 topographic maps and Landsat imagery. This study concluded that the number and combined area of lakes positioned on the 20th to 21st century moraines in proximity to glaciers exhibited the largest change, while those positioned on the older moraines changed the least. The study stressed that opposite trends in lake evolution can be observed within the same relatively small region, particularly with regard to lakes positioned on the young moraines. (g) Kokarev and Shesterova (2014) assessed changes in glacier area in the southern Zhetysu Alatau, where they identified 190 lakes with the total area of 6 $km^2$ as in 2000 but did not provide any analysis of lake distribution and evolution.

(Kapitsa et al., 2017) provide an inventory of lakes for 2002-2014 and their observed and future evolution in the Zhetysu Alatau and an assessment of their hazard potential using remote sensing (Landsat imagery) and GlaTop2 model as well as identifying areas where future lakes could develop. Fifty lakes, whose potential outburst can damage existing infrastructure, were identified. Results from (Vassiliy Kapitsa et al., 2017) show that in 2002 there were 599 lakes with a combined area of 16.26_ 0.85 $km^2$ and in 2014 there were 636 lakes with a combined area of 17.35_ 0.92 $km^2$. In 2002, the largest measured lake area was 1.03 $km^2$ and the smallest was 0.0007 $km^2$. Lakes were positioned within the elevation bands of 2220–3660 and 2220–3690m in 2002 and 2014 respectively; and the majority of lakes (56% and 52% of their combined area respectively) were positioned between 3100m and 3400m a.s.l.

(Kapitsa et al., 2018) (IN RUSSIAN) provide a catalogue of glacial lakes developed using remote sensing and field work in 2009-2017 for the Ile Alatau from which GLOF hazard assessment was analyzed.

(Bolch et al., 2011) identified 66 lakes for the 1970s, and 132 lakes in 2007 in the northern Tien Shan, Ile Alayau and Kungöy Ala-Too region. The number of lakes almost doubled between 1972 and 2000. Bolch and colleagues did a semi-automatic identification and monitoring of glacial lakes using band rationing and the normalised difference water index (NDWI) based on multi-temporal space imagery from the years 1971 to 2008 using Corona, ASTER and Landsat data. They manually edited the results when required. One of the lagest lakes found was lake Bolshoje Almatinskoje, which is close to the big and heavily populated city of Almaty. It developed after a rock avalanche and was dammed by artificial dam. About 60% of the identified lakes are in direct contact with the glacier ice. The overall area of the lakes increased from about 2.56 $km^2$ to about 3.44 $km^2$ and the estimated volume from ≈42.4 × $10^6$ $m^3$ to ≈50.1 × $10^6$ $m^3$ (1972–2007). Both the absolute lake area and the change rate increased from the periods 1972–2000 to 2000–2007. However, during this period Bolch et al. (2011) also observed that several lakes lost surface area or disappeared completely. A possible cause of this decrease are lake drainages, some of which may have occurred rapidly causing a GLOF, as e.g. in Kishi and Ulken Almaty valleys in 1973 and 1977 (Plekhanov et al., 1975, Popov, 1978, Vinogradov, 1977). (Blagovechshenskiy et al., 2015) compile a catalogue of 186 glacial lakes in Ile Alatau and 577 lakes in Zhetysu Alatau using satellite images together with aerial visual surveys and field surveys. They also included the bathymetric data for 35 glacial lakes see point “methods used” of this section for more detail).

Kazselezashchita in the 70-80s carried out work on the creation of passports for all moraine lakes in the basins of the Ile Alatau (Uzynkargaly, Shamalgan, Kaskelen, Aksay, Kargaly, Ulken and Kishi Almaty, Talgar and Esik rivers).

In 1986 Popov N.V. a dissertation was written on the topic “Study of lakes in the glacial zone of the south-east of Kazakhstan in order to assess the possibility of their breakthrough and monitoring the mudflow hazard”. The paper considers lakes in the glacial zone of the southeast of Kazakhstan, the stages of studying lakes and analyzing their distribution. The relationship between the emergence and development of near-glacial lakes and the degradation of glaciers in the southeast of Kazakhstan is also considered. A classification of lakes in the glacial zone has been developed, and the mechanism of catastrophic emptying of lakes has been identified.

In 2003, the Institute of Geography under the leadership of Medeu A.R. the work on the topic "To carry out cataloging of moraine lakes of the high-mountainous zone of the Zailiysky Alatau" was completed.

(Blagovechshenskiy et al., 2015) compile a catalogue of 186 glacial lakes in Ile Alatau and 577 lakes in Djungarskiy Alatau using satellite images together with aerial visual surveys and field surveys. They also included the batimetric data for 35 glacial lakes see point “methods used” of this section for more detail).

Catalogue of all moraine lakes in Kazakhstan was started in 2015 and was carried out by specialists of KMP services using satellite data from Google Earth, SAS Planet Release and according to the available data from bathymetric works, ground and aerial surveys. These works are ongoing, at present, additions and changes are being made to the “Passports of glacial-moraine lakes”.

In the period up to 2015, passports for moraine lakes were drawn up only for the most dangerous moraine lakes.

Dangerous moraine lakes were identified only based on the results of aerial and ground surveys. In the territories of the South Kazakhstan, Zhambyl, East Kazakhstan regions, aerial surveys for moraine lakes were not carried out, and if they were carried out, it was not detailed. This work started just in 2016.

According to the results of aerial and ground surveys in 2021, the number of “Passported” moraine lakes was 970:

- in the city of Almaty and Almaty region (Ile, Kungey, Teriskey and Zhetysu Alatau, ridges of Saryzhaz) - 752;
- in the Zhambyl region (Talas Alatau) - 27;
- in the Turkestan region (ridges Ugam, Karzhantau) - 45;
- in the East Kazakhstan region (ridges of Ivanovsky, Listvyaga, Sauyr, Southern Altai, Tarbagatai, Sarymsakty) - 146.

● **Temporal and spatial resolution of the mapping and monitoring.**

Mudflow hazard typification map (made by the Institute of Geography) made at a very high scientific level and allowing a fairly accurate assessment of the full potential of mudflow hazard of the Almaty metropolis and the Almaty region, which can be useful to the population and various organizations.

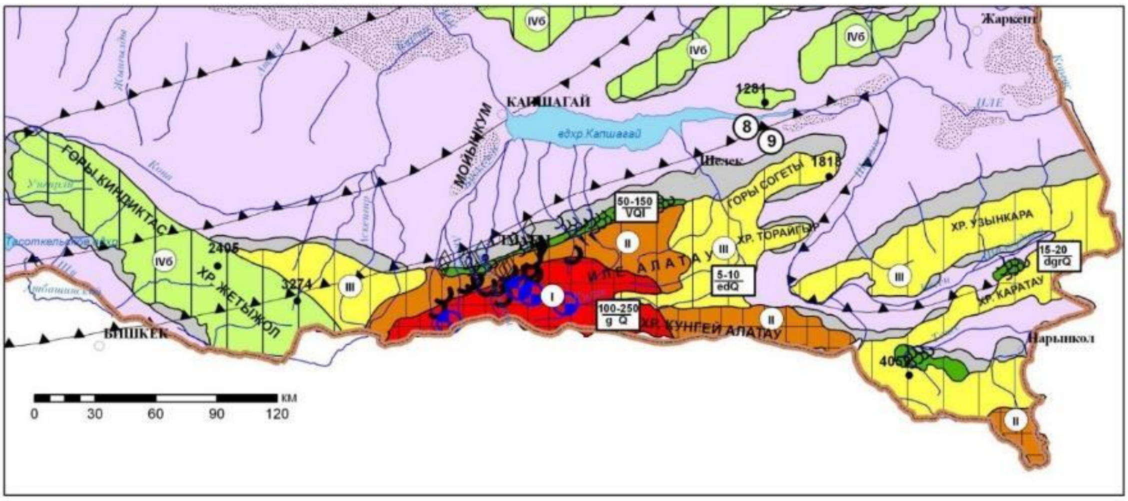



Figure 2. Mudflow hazard typification map of Ile Alatau (*Compiled by A.R. Medeu, N.F. Kolotilin*), legend is given below.

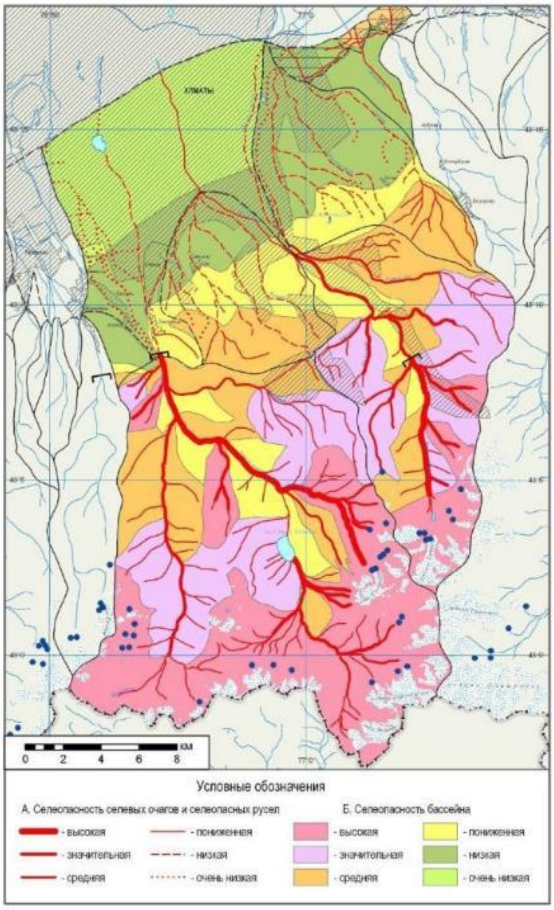
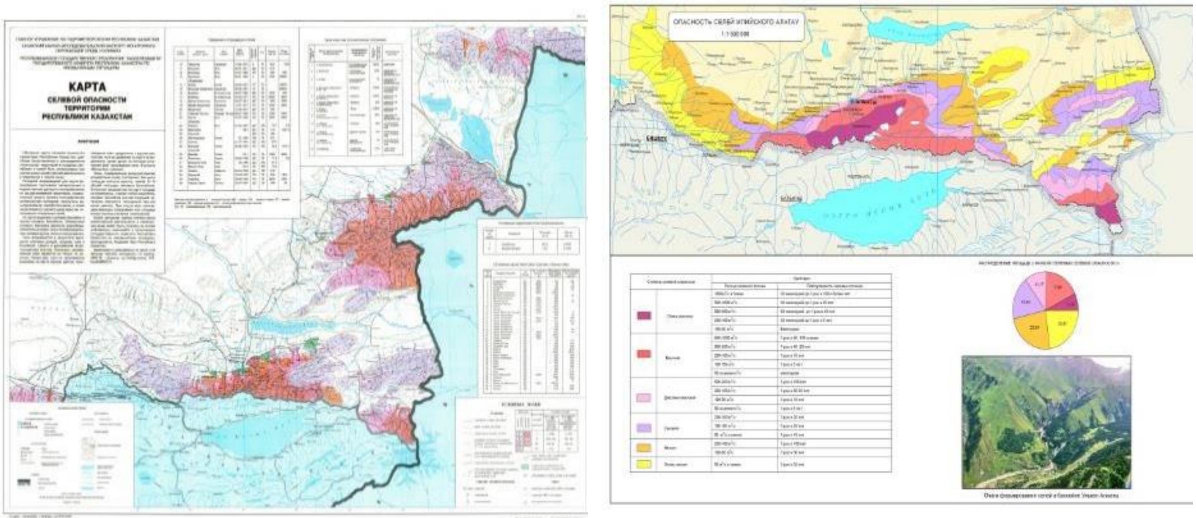




Figure 3. A fragment of a detailed map of the mudflow hazard of Almaty and the region, scale 1: 100,000 along the riverbeds and high mountains

Figure 4. Mudflow hazard map of Ile Alatau. Fragment - Kishi and Ulken Almaty basins (compiled by A.R. Medeu, T.L. Kirenskaya)

As one of large works which can be used at risk assessment of economic activity in mountain and foothill zones in the territory of Kazakhstan Republic and gives information on distribution of mudflow territories is - “The map of rainfall generated mudflows danger of the Republic of Kazakhstan territory” (Stepanov & Talanov etc., 1996). On this map are presented groups of mudflow basins, elements of mudflow basins are included catchment areas, mudflow lakes, mudflow centers, parts of mudflow basins and alluvial fan of mudflows, directions of mudflows moving and 4 categories of mudflow hazardous in (Fig. 5 (a)). On the “Mudflow dangerous areas” map including in the Atlas of emergency situations of Kazakhstan Republic released in 2010, are specified degrees of mudflows dangerous and its relating criteria (height, slope, coefficient of prevalence of mudflow center, sum of annual rainfall), genesis and types in (Fig. 5 (b)).

a) b)




a) Map of mudflow danger of the territory of the Republic of Kazakhstan (1996) b) Mudflow danger regions of Kazakhstan Republic (Medeu, 2009)

- **How are locations for monitoring selected**

Many studies in Kazakhstan focus on the Ile Alatau Mountain region as it is a densely populated area and affects the big city of Almaty with over 2,5 M inhabitants. The Djungarskiy Alatau region also holds studies as lakes are particularly widespread and glacier retreat rates are highest for the region (Severskiy et al. 2016).

Monitoring of hazardous natural processes is of paramount and supremely importance in the mudflow monitoring system. Considering the rapid and largely unpredictable nature of the formation of mudflows, the observation network must meet the following basic organizational requirements: maximum coverage of protected areas and dangerous objects; reasonable sufficiency of saturation of river basins with observation posts; maximum efficiency of information transfer, with the subsequent creation of an automated monitoring and warning system. Observation network of Kazselezashchita for mudflows in the Almaty city region was created based on the already existing State hydrometeorological network.

Monitoring of the state of moraine lakes, mudflows, hydrometeorological conditions and the occurrence of mudflows was carried out at specialized posts, as well as with the help of regularly conducted reconnaissance, ground and airborne surveys. Subsequently, the long-term practice of organizing a departmental observational network of Kazselezashchita made it possible to develop a certain methodology for placing posts (in basins, from moraine lakes and mudflows to alluvial fans and settlements, on critical engineering protective structures).

Moraine-glacier complexes of Ile and Kungey Alatau

The number of observation posts and their location is determined by the degree of mudflow hazard of the basin, the presence of economic facilities, residential buildings located in hazardous areas, and dispatch centres can control the situation in a group of adjacent pools. Reception and analysis of data is carried out by the Main control centre in the city of Almaty. The specifics of the work of mudflow protection services provides for the placement of posts on especially critical protective structures and complexes.

Aerial reconnaissance surveys of territories are carried out regularly throughout the entire mudflow hazard period and are aimed at obtaining additional information about the state of lakes, other mudflow objects, as well as a background assessment of mudflow hazard. In addition to assessing the state of high-mountain lakes, aerial visual surveys make it possible to observe the very process of formation of mudflows. Every year, about 250 hours of flight time are used for aerial helicopter overflights of dangerous territories, airdrops, maintenance of high-mountain posts, delivery of cargo to emergency teams and other work.


Aerial survey works

Ground reconnaissance surveys of moraine-glacial complexes, the state of lake cofferdams, surface runoff channels and mudflow centres are carried out both by observation teams working near objects and by reconnaissance teams of specialists in case of an increase in the likelihood of a breakthrough of one or another object. In the latter case, the activities are more detailed and may contain elements of engineering hydrological, geodesic and other necessary studies.



Reconnaissance work on the moraine lakes

In the Monitoring and Warning Service of the State Institution "Kazselezashchita" in the 70-80s, there were more than 250 observation posts, but after 1990 their number was halved due to the collapse of the USSR. To date, there are 63 regular, 53 seasonal stations, 24 avalanche routes in the State Institution "Kazselezashchita", and temporary observation stations are set up in cases of a threat of emergencies.

Observations of the state of high-mountain lakes, mudflow objects, hydrometeorological conditions and the occurrence of mudflows were carried out at specialized stations, as well as with the help of regularly conducted ground and aerial surveys. Work has already begun on organizing an automated monitoring network for the basins of the Aksay, Kargaly, Ulken and Kishi Almaty, Korgas rivers with a total number of more than 40 automated stations.

- **What methods are used**

*Taken directly from (Bolch et al., 2011):* Glacial lakes that develop in remote mountainous areas are often difficult to access and field studies are laborious and cost-intensive. Therefore, remote sensing data and GIS are ideal tools for studying and monitoring glacial lakes and assessing their hazard potential (Buchroithner 1996; Huggel et al. 2003; Schneider 2004; Kääb et al. 2005; Quincey et al. 2005; Bolch et al. 2008). Recently, several studies demonstrated the suitability of optical remote sensing data for detection of glacial lakes in an automated way (Huggel et al. 2002; Quincey et al. 2005; Bolch et al. 2008; Frey et al. 2010). The aforementioned literature indicates that one of the main drawbacks in the automated methods is the difficulty in differentiating the lakes with turbid water and the fact that the areas with cast shadow are usually misclassified. While the latter can be addressed by applying a shadow mask using a precise digital elevation model (Huggel et al. 2002), so far no real promising method for turbid water exists in the literature. Hence, manual checking and editing is still essential. Manual digitizing is also required for panchromatic data such as aerial imagery and declassified intelligence data such as Corona. A digital elevation model (DEM) of the study area is essential to obtain the geomorphometric data of the glaciers, glacial lakes and its surroundings and especially for modeling of the probable outburst path. The freely available near-global void-filled SRTM3 DEM and the ASTER GDEM are a good choice if no other detailed local DEM is available (Frey et al. 2010). The SRTM3 DEM and ASTER derived DEMs were shown to be suitable with the limitation that the elevation and characteristics of smaller features such as the lateral moraines and deep gorges may not be accurately and precisely depicted (Fujita et al. 2008; Huggel et al. 2003; Kamp et al. 2005). Additional errors occur especially on steep slopes due to low contrast in areas with cast shadow in the used imagery (GDEM) and layover and foreshortening of the radar data (SRTM DEM, Kocak et al. 2004).

In their study, Bolch and colleagues (Bolch et al., 2011) did a semi-automatic identification and monitoring of glacial lakes using band rationing and the normalised difference water index (NDWI) based on multi-temporal space imagery from the years 1971 to 2008 using Corona, ASTER and Landsat data. They manually edited the results when required. For a thorough description of the data and methods used see (Bolch et al., 2011).

(Kapitsa et al., 2017) studied changes in abundance and area of lakes in the Zhetysu Alatau region between 2002 and 2014 using Landsat imagery. In this study, automated mapping of lakes was initially performed using various band combinations but did not produce satisfactory results because the method frequently misclassified melting glaciers as lakes and failed to distinguish lakes with high water turbidity. Water turbidity is particularly typical of the lakes developing on newly formed moraines, which are abundant in the region. Moreover, small lakes cannot be mapped using automated techniques. These are also abundant in the region frequently forming vertical sequences or cascades where several lakes either have a hydraulic connection or are located in proximity at different elevations. The outburst of one lake could trigger the outburst of multiple lakes creating a debris flow whose volume significantly exceeds the initial outburst (Evans and Delaney 2015). Thus, they mapped lakes manually using channels 7, 4 and 2 of Landsat 7 and channels 3, 5 and 7 of Landsat 8. The use of the panchromatic channel 8 with 15m resolution, for manual mapping, enabled Kapitsa and colleagues to lower the threshold of digitization from 2000 to 675m$^2$. In their study, all mapped lakes were assigned to one of following types : Type 1 – contact lakes developing at glacier tongues, Type 2 – proglacial morainic lakes forming on the 20th to 21st century moraines in close proximity (typically within 500 m) to but without contact with glacier tongues, Type 3 – morainic lakes positioned in depressions on the LIA or older moraines, and Type 4 – dammed lakes forming due to the damming of rivers and streams by rocks. No ice-dammed lakes were found in the region. This classification was considered by Kapitsa and colleagues to be less detailed than the lake classification by Popov (1986) and Medeuov et al. (1993); however, analysis of Landsat imagery did not enable them a more-detailed discrimination. (A. R. Medeu et al., 2018) (IN RUSSIAN) show the results of research on automated monitoring of mudflow hazard in the Ile Alatau. The conditions for the formation of mudflows, mudflow activity, mudflow hazard and mudflow monitoring are considered. The book is intended for specialists in the prevention of natural emergencies, scientists and designers.

(Blagovechshenskiy et al., 2015) compile a catalogue of 186 glacial lakes in Ile Alatau and 577 lakes in Zhetysu Alatau using satellite images together with aerial visual surveys and field surveys. They also included the bathymetric data for 35 glacial lakes. Glacial lake identification and inventorying was done manually using Landsat satellite images with panchromatic channel and Aster images; a 30m resolution Aster digital terrain model and topographical maps 1:50,000. They also held a field survey (August 2002). The results were checked during aerial visual surveys from a helicopter. Then they determined the morphometric characteristics of the lakes using satellite images and topographical maps with ArcGis 9.3.1. The Kazakhstan Mudflow Protection Service and Institute of Geography measured the area and water volume of 35 lakes using echo sounder and GPS-receiver. Comparison of the lake areas measured in the field with the data obtained from the satellite images showed a difference of no more than 5%. In the lake inventories they differentiated proglacial lakes and moraine lakes. They assumed the former to be in contact with or very close to a glacier tongue and receiving water from it and being dammed primarily by young ice-cored moraines; whereas the latter are located in older moraines and further away from current glacier tongues so without direct hydrological connection to glaciers.

# 5. Hazard and Risk Assessment

- **Scale of the assessments**

(Medeu et al., 2020) study Ile Alatau as they consider this region to be the most mudflow hazardous mountain region of the Republic of Kazakhstan.

(Plekhanov et al., 2019) cite as an example, based on the data of the Committee for Emergency Situations of the Ministry of Internal Affairs of the Republic of Kazakhstan in 2014, the studies of the exposure of the Republic of Kazakhstan to natural emergencies for the period 2004–2013 and determined that 93 different Extreme Hydrological Phenomena occurred in the republic during this period: 58 floods, 9 spring floods, 5 flooding areas, 15 wind surges, 3 mudflows, one ice-hazards, one dangerous slope runoff, and one high groundwater level rise. The general consequences of these events were: 45 dead and 13,055 affected people, as well as direct economic damage - 41.36 billion tenge (or 275.7 million USD). Probably, the magnitude of the damage is significantly underestimated in comparison with its real value, since only in 1993, flood damage was twice as high. On the environmental damage caused by floods, there is no information because in Kazakhstan no special studies of this problem have been undertaken. (Plekhanov et al., 2019) consider climate as the most important factor determining the spatial and temporal patterns in the formation and flow regime on the territory of the republic, including the occurrence of Extreme Hydrological Phenomena. According to the RGP “Kazgidromet” over the past 75 years, in Kazakhstan there has been an average increase in temperature by 0.280 and a decrease in the amount of precipitation by 0.2 mm every 10 years.

(Kapitsa et al., 2017) identified fifty lakes whose potential outburst can damage existing infrastructure in the Zhetysu Alatau region, mainly NW and SW sectors.

(Kapitsa et al., 2018) (IN RUSSIAN) provide a risk assessment analysis of glacial lake outbursts and formation of debris flow in the Ile Alatau based on the catalogue of glacial lakes developed using remote sensing and field work in 2009-2017. Climatic changes were assessed using data from six meteorological stations located between 1100 m and 3450 m a.s.l. They identified seventeen lakes as dangerous using methods employed by the Kazakhstan State Agency for Mudflow Protection and those proposed by Huggel et al. (2002). The potential discharges resulting from the outburst of these lakes were estimated.

(Zapparov et al., 2021) consider the developed method of Kazselezashchita with the additions and changes to be the most acceptable when carrying out certification of moraine-glacial lakes, reconnaissance work and when carrying out operational measures to reduce the breakthrough hazard of moraine lakes. Determination of the potential danger of a lake breakthrough will provide real assistance in preventing the occurrence of uncontrolled natural processes in the glacial-moraine complex. It is proposed to introduce an additional category "very dangerous lake" for outburst-hazardous moraine lakes in the presence of a settlement with a population of more than 500 people or a strategically important object in the mudflow risk zone.

As a result of the studies carried out to develop the breakthrough hazard criterion, outburst-hazardous lakes were identified, information was obtained on the morphometry and morphology of lake bowls and the hydrological regime for individual lakes, and a list of dangerous mountain lakes was determined, where measures should be taken to eliminate their possible breakthrough. 333 lakes and temporarily empty lake basins were registered in the studied mountainous areas of the Almaty region. Including along the Ile Alatau – 188, along the Kungei Alatau – 86, Terskey Alatau - 14 and 45 lakes on the Saryzhaz ridge.

Table 1 - Distribution of moraine-glacial lakes with an indication of their outburst hazard

| **Mountains** | **GLOF susceptibility** | | | | |
|---|---|---|---|---|---|
| | **Very high** | **High** | **Medium** | **Low** | **Developing Lake** |
| Ile Alatau | 11 | 25 | 38 | 21 | 93 |
| Kungey Alatau | 3 | 17 | 13 | 35 | 18 |
| Terskey Alatau | | | 6 | 8 | |
| Saryzhaz Ridge | 1 | 7 | 11 | 9 | 17 |

The problem of protection from mudflows, avalanches and landslides appeared almost simultaneously with the beginning of the development of mountainous and foothill areas of Kazakhstan. In retrospect, its solution is the history of the design and construction of individual structures designed to protect specific objects (50-60s of the last century), the development and implementation of General schemes for protection against mudflows, avalanches, and landslides of individual territories (60-70-s). years), Integrated schemes for the protection of settlements, enterprises and other objects and lands from mudflows, snow avalanches, landslides and landslides (70-80s) and the Consolidated scheme of anti-mudflow, avalanche and landslide measures of the Kazakh SSR, which in 1990 was approved by the government as a general.

"Adjustment of the General Scheme for protection against snow avalanches, landslides and mudflows in the territories of the cities of Almaty and Shymkent, Almaty, Turkestan, Zhambyl and East Kazakhstan regions" was included in the implementation points of the Roadmap "Comprehensive plan to ensure mudflow, late and avalanche safety for 2020- 2024" which was signed by 4 ministries.

- **What institutions are undertaking the hazard and risk assessment**.

In 1969, the Moscow State University published a bibliographic index "Mudflow phenomena on the territory of the USSR and measures to combat them ", which covered the literature on this issue published from the middle of the 19th century to 1967, inclusive. Over the past decades, a number of international conferences on mudflows have been held from which monographs where provided such as "Map mudflow hazardous regions of the USSR ". Large-scale experiments were carried out in Kazakhstan with artificial mudflows, several outburst-hazardous lakes and a number of mudflow protection structures were built. This led to a significant growth in the publication on mudflow-related literature. (Ними, 2008) propose an index that includes works published from 1968 until 1991., as well as works that were not included for various reasons in the previous index. All in Russian, Ukrainian and in other USSR languages. This index goes until 1991 as it was the end of the existence of the USSR. It has five sections: Section I includes works on mudflow conferences and meetings, monographs, specialized collections, chronicles, normative documents, copyright certificates (patents); Sections II and III include theoretical works; Section IV includes applied works; and finally Section V compiles regional characteristics of mudflow formation.

(A. P. Medeu et al., 2020): Systematic scientific research of mudflows in the Ile Alatau is carried out since 1950s, when a mudflow party was created in the hydrometeorological service and research institute (KazNIGMI). Mudflow studies were carried out by "Kazselezashchita", as well as at the Institute of Geography and the Institute of Geological Sciences of the Academy of Sciences KazSSR. "Kazselezashchita" was created in 1973 specifically to provide protection from mudflows.

(A. P. Medeu et al., 2020) and (Medeu et al., 2019): The Institute of Geography, from the Ministry of Education and Science of the Republic of Kazakhstan in Almaty holds research around hazard and risk assessments. (Kapitsa et al., 2017) mention the Kazakhstan State Agency for Mudflow Protection (KSAMP); and the Newton – al-Farabi Fund for the project “Climate Change, Water Resources and Food Security in Kazakhstan”

«Kazselezashchita», Committee Emergency Situations of Ministry of Internal Affairs of the Republic of Kazakhstan (Almaty) was established in Kazakhstan in 1973 and worked for the decrease of the recurrence-rate of glacial debris flows in Ile Alatau since the end of the 1970s. Its efforts were particularly active since the end of the 1990s. To date the emptying of lakes is done by using high-capacity siphons and pumps. Small-sized bulldozers and excavating machines are used in digging discharge channels.

(Plekhanov et al., 2019) describe that in 2015, in order to reduce disaster risks in Kazakhstan with the assistance of UNDP, they updated the “Plan of preparedness of the Republic of Kazakhstan for natural emergencies” and the methodological foundations were developed and introduced into the state system of civil protection of the republic: “National Situational Safety Analysis of the Republic of Kazakhstan from natural and man-made disasters”. Then, the Committee on Emergency Situations of the Ministry of Internal Affairs of the Republic of Kazakhstan also started working to attract international expertise in the fields of innovative technologies for flood protection engineering and disaster risk management with the participation of the Center for Emergency Situations and Disaster Risk Reduction in Almaty as part of the Sendai Framework for Risk Reduction disaster for the years 2015-2030.

As a result of the implementation of various projects and protection schemes in Kazakhstan, more than 80 protective structures have been built and are currently in operation, including 21 anti-mudflow dams, 56 linear structures (stabilized channels, bank protection, canals, flumes, dams, low-pressure dams, etc.). Currently, work is underway on the construction of mudflow protection structures on the Aksay, Ulken Almaty, Korgas rivers, as well as bank protection works on the Korgas river.

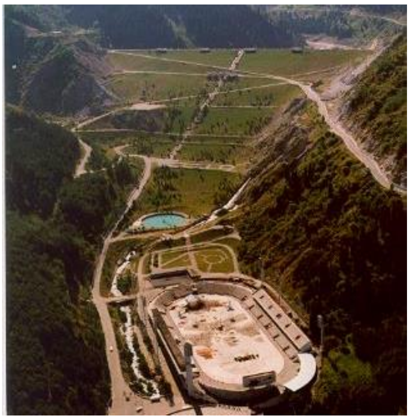
The main part of the constructed structures has played a positive role in reducing damage during the passage of mudflows and is ready to perform their functions in the future.

Several structures were destroyed by mudflows, avalanches and landslides. In addition to the construction of protective structures provided for by mudflow protection schemes, Kazakhstan actively carried out work to prevent them by controlled emptying of outburst-prone mountain lakes. Thanks to them, in some cases, the danger of mudflows was eliminated, and in others, the danger of mudflows was significantly reduced.

Anti-mudflow dam on the Kargaly River

Mudflow retention dam on the Talgar River

Mudflow catcher struction on the Kishi Almaty River



Mudflow retention dam "Medeu" on the Kishi Almaty River

- **Assessment methods used**

(Kapitsa et al., 2017) identify glacier overdeepenings where future lakes could form using GlabTop2 (glacial bed topography version 2) to simulate ice thickness and subglacial topography using glacier outlines for 2000 and SRTM DEM. They compared the modelled future lake formation with the inventoried formation of new lakes between 2000 and 2014 and found that 67% of modelled new lakes did indeed form. They also identified locations where hazardous lakes may develop in the future.

(Kapitsa et al., 2017) followed the three-tier methodology of assessment of hazard potential of lakes proposed by Huggel et al. (2002), and, having completed level 1 (basic detection of lakes), they focused on level 2, i.e. consideration of criteria which can be derived from Landsat imagery and both SRTM and ASTER GDEM. These criteria and the order of their consideration were (i) lake type, (ii) presence of cascade of lakes, (iii) lake area (as an indicator of peak discharge), (iv) distance to infrastructure, (v) average slope, and (vi) presence of slopes of 45º and steeper in proximity to the lake. They considered as potentially hazardous lakes in contact with glaciers and those located on young moraines. Lake area is frequently used as a proxy for peak discharge (Huggel et al., 2002); however, there is no uniformly accepted threshold for a critical lake area and this is often set according to the previous GLOF events (e.g. Cook et al., 2016). Wang et al. (2013) used a threshold of 100 000m$^2$, assessing potentially dangerous lakes across the Tien Shan, while the Kazakhstan State Agency for Mudflow Protection (KSAMP) uses a threshold of 10 000m$^2$ in the Ile Alatau (Bizhanov et al., 1998) but does not specify any threshold for the study region. For single lakes, (Kapitsa et al., 2017) set a threshold of 20 000m$^2$ based on the consideration that the lakes in the Aksu and Kora valleys, whose previous outbursts significantly damaged the infrastructure, had areas of approximately 20 000m$^2$ (Medeuov et al., 1993) and that the valleys in the Zhetysu Alatau are approximately twice the length of the valleys in the Ile Alatau. They considered both proglacial and young-moraine lakes, irrespective of their size, as potentially dangerous if they were part of a cascade of lakes with further lakes located on the potential flood path. They also considered lakes as potentially dangerous if they had a hydrological connection to downstream settlements, infrastructure and agricultural fields located within 60 km distance. They assumed a $3^0$ slope threshold as a condition for debris flow propagation and slopes steeper than $45^0$ were considered as particularly dangerous (Alean, 1985; Bolch et al., 2011; Cook et al., 2016). They generated slope maps from SRTM GDEM and ASTER GDEM2. To assess the severity of potential GLOF events, Kapitsa and colleagues estimated lake volumes using an empirical relationship between lake area and volume derived from bathymetric measurements of 32 proglacial and moraine dammed lakes, with areas ranging between 2000 and 200 000$m^2$ (in 2009–2014) at the end of the ablation seasons (late August–September) (Medeu and Blagoveshenskiy, 2015).

(Blagovechshenskiy et al., 2015) used satellite images together with aerial visualization and field surveys to obtain the necessary information on lakes, glaciers and slopes to carry out a GLOF hazard assessment according to four factors: (1) lake characteristics (the Kazakhstan Mudflow Protection Service considers a glacial lake to be dangerous if its volume exceeds 100,000 $m^3$), (2) dam characteristics (lakes dammed by young moraines with an ice core show the highest possibility of outburst, e.g. Proglacial lakes ), (3) characteristics of the valley below the lake (a lake outburst transforms into a mudflow only if the valley below has slopes of more than $15^0$ spreading for more than 500m), and (4) potential damage from the mudflow (potential damage depends on the existence of social and economic objects and the impact and protection level of them). Taking into account these factors they found 14 most hazardous lakes; 6 in Ile Alatau and 8 in Zhetysu Alatau (see Table 3 in part “Overview of hazard and risk hotspots”).

A similar explanation of key factor contributing to the hazard risk of a glacial lake using remote sensing data is provided by (Bolch et al., 2011) here presented in **Error! Reference source not found.**.

Table 2 Taken from (Bolch et al., 2011). Key factors contributing to the hazard risk of a glacial lake and its investigation using remote sensing data (based on Richardson and Reynolds 2000; Huggel et al. 2002; Quincey et al. 2005; Bolch et al. 2008)

| Characteristics group | Factor | Remote sensing data source and applicable techniques | Suitable for automatisation | References |
|---|---|---|---|---|
| Lake characteristics | Lake area and volume | Detection using multi-temporal multi-spectral (MS) satellite data | Yes | Wessels et al. (2002), Huggel et al. (2002) |
| | Rate of lake formation and growth | Change detection using multi-temporal (MT) and MS satellite data | Yes | Bolch et al. (2008) |
| Glacier characteristics | Fluctuations of the glacier | Investigation of area and volume change of the glacier based on MS and MT satellite data, MT digital elevation models (DEMs) | Yes | Bolch et al. (2010, 2011), Paul et al. (2002), Aizen et al. (2006) |
| | Activity of the glacier | Derive glacier velocity using feature tracking or DInSAR based on MT optical or radar data | Yes | Kääb (2005), Luckman et al. (2007), Scherler et al. (2008), Bolch et al. (2008) |
| | Geomorphometric characteristics of the glacier | Geomorphometric DEM analysis, slope classification | Yes | Bolch et al. (2007), Quincey et al. (2005) |
| Characteristics of the lake surrounding | Freeboard between lake and crest of moraine ridge | Geomorphometric DEM analysis | Partly | |
| | Width and height of the moraine dam | Geomorphometric DEM analysis | Partly | |
| | Stability of the moraine dam/ presence of dead ice in the moraine dam | Investigation of surface deformation based on MT DEM analysis, permafrost modelling | Partly | Fujita et al. (2008) |
| | Possibility of mass movements into the lakes | Mapping of ice cover and geology using MS data, Geomorphometric DEM analysis of the surrounding catchment areas, flow modelling | Yes | Huggel et al. (2003), Salzmann et al. (2004), Allen et al. (2009) |
| Impact of an GLOF to downstream areas | Affected area | Flow modelling | Yes | Huggel et al. (2003), Mergili et al. (2011) |
| | Infrastucture down-valley | Detection of human infrastructure based on MS satellite data analysis. | Partly | |

(Medeu et al., 2019) look into long-term research of debris flows activity in Ile Alatau over a period of more than 100 years to obtain quantitative characteristics to asses debris flow risk, debris flow hazard zoning, to develop debris flow control-measures and designing of protection structures. Such quantitative characteristics include the recurrence of debris flows of different genesis as well as their volumes, flow rates and velocities. They used results from analyzing past debris flow activity to compile debris flow hazard and risk maps for the city of Almaty, develop an early warning system and project debris flow protection dikes. In the future, Medeu and colleagues plan to compile maps for all debris flow-hazardous basins of Ile Alatau.

(Medeu et al., 2018) (IN RUSSIAN) provide a mudflow hazard map for the Kishi and Ulken Almaty river basins at the level of riverbeds and streams. They address the assessment and mapping of mudflow danger in those river basins. They consider characteristics such as the way of flow, the limits of distribution of mudflows, different volumes and the repeatability of the events.

(Medeu et al., 2020) (IN RUSSIAN) recall how mudflow hazard maps were compiled in 2018-2019 by the Institute of Geography under the instructions of the Department of emergency situations of the city of Almaty. The 1:25 000 mudflow hazard and risk maps for the Kishi and Ulken Almaty river basins, as well as for Kargaly and Aksai rivers were compiled using GIS technologies based on many years observations, field research and satellite images. The mudflow hazard maps show the paths of movement and the boundaries as well as various volumes and frequencies. Mudflow risk maps were assessed by categories: social, economic and ecological. Mudflow risk maps were compiled on the basis of mudflow hazard maps and a list of objects potentially affected. Damage and risk calculations were performed for each object subject to the impact of mudflows. The mudflow impact zones, marked on the mudflow hazard maps, were differentiated by three levels of risk (low, moderate, high), depending on the severity of the consequences of mudflow impacts and their frequency. Repeatability of emergency situations was estimated by the frequency of mudflows.

(GAPHAZ, 2017) recognize the need for a structured and comprehensive approach to hazard assessment underpinned by latest scientific understanding, and has produced a technical guidance document as a resource for international and national agencies, responsible authorities and private companies. These guidelines focus on hazards directly conditioned or triggered by contemporary changes in mountain glaciers and permafrost, including GLOFs. They recommend to consider the following principles when assessing hazards and risks associated with glaciers and permafrost in mountains (GAPHAZ, 2017): (1) Global change, (2) Chain reactions and interactions, (3) Monitoring, (4) Integrative risk assessments, (5) Remote sensing, (6) Socio-economic context. These guidelines suggest that inventories of past catastrophic mass movements are a fundamental prerequisite for the assessment of hazards and risks, over a minimum span of 30 years. Through the investigation of the distribution, type and pattern of past hazard events, the understanding of triggering and conditioning processes can be improved as well as the susceptibility assessment optimized, and the impacts better constrained.

- **Data used**

For data collection (Medeu et al., 2019) plan to use the system for automated monitoring of debris flows to start operations in 2020. In addition to ground-based observations, they will use satellite images, including Kazakhstan satellite imagery to access data on debris flows for high-mountain hard-to-reach regions.

- **Overview of hazard and risk hotspots**

Table 3 taken from (Blagovechshenskiy et al., 2015): the most hazardous lakes in Ile and Zhetysu Alatau mountain ranges.

| **Mountain Range** | **Valley (lake name)** | **Hight (m a.s.l)** | **Volume ($m^3$)** | **Past events** | **Potential damage** | **Preventive measures already** |
|---|---|---|---|---|---|---|
| Ile Alatau | Kaskelen | 3430 | 120,000 | 1980 | Roads, recreation area, Kaskelen town | dam |
| | Big Almaty (Kumbel) | 3550 | 250,000 | | Roads, houses, hotels, restaurants | Dam for Almaty city |
| | Little Alamty (Mametova) | 3600 | 180,000 | | Dam infrastructure | Medeu dam |
| | Talgar* (cascade of lakes)<br>Toguzak<br>Kalesnika<br>Solnechnoye | <br><br>3480<br>3400<br>3410 | <br><br>206,000<br>150,000<br>190,000 | | Infrastructure, natural reserve | Dam for Talgar town |
| | Yesik (Zharsay) | 3570 | | 1963 | Recreational zone and natural sanctuary | Lake bowl is empty but drainage net can be fast filled |

| Mountain Range | Valley (lake name) | Hight (m.asl) | Volume ($m^3$) | Past events | Potential damage | Preventive measures already |
|---|---|---|---|---|---|---|
| Zhetysu Alatau | Korgas*(cascade of lakes)<br>Kapkan lake<br>Boskul<br>Kazankol | <br><br>3440<br>3120<br>2230 | <br><br>3,7M<br>2,1M<br>5,2M | | International Center of Border Trading | Being designed |
| | Osek | 3400 | 2,7M | | Lesnovka village | none |
| | Asku<br>1<br>2<br>3 | <br>3250<br>3170<br>3180 | <br>2,2M<br>1,6M<br>1,7M | | Hydroelectric power station and Zhansugurov town | none |
| | Sarkan<br>1<br>2 | <br>3440<br>3240 | <br>2,5M<br>1,2M | 1982 | Sarkan town | Dam for town |

Several publications are found on Ile Alatau Mountain Range (northern range of Tien Shan mountains) with settlements, including Almaty city, with the a total population of about 2 M inhabitants in the foothill zone of the northern slope (Yafyazova, 2011) (Medeu et al., 2020) (Narama, et al., 2009) (Bolch et al., 2011).

(Kapitsa et al., 2017) identified fifty lakes whose potential outburst can damage existing infrastructure in the Zhetysu Alatau region, mainly in the NW ansd SW sectors. Thirty two of the potentially dangerous lakes are part of cascades of lakes including the two largest lakes in the sample and those in the Aksu (N 45) and Sarkand (N 43) valleys, which burst out in 1970, 1978 and 1982 respectively, causing overtopping of the lakes located at lower elevations. Lake Kapkan (N 25), identified as dangerous and the only lake in the Zhetysu Alatau that has been periodically lowered since August 2014, belongs to a cascade of six lakes. Four of those lakes are located at lower elevations on the potential flow path to the town of Khorgos hosting the recently established International Trade Centre (Medeu et al., 2013). Lakes N 15 (contact lake) and 17 (young moraine dammed lake) in the Aksu catchment are positioned at the top of the largest cascade of lakes in the Zhetysu Alatau. The largest lake (N 16) in this cascade has an area of 185,000$m^2$. The outburst of Lakes 15 ad 17 can potentially cause overtopping of other lakes downstream and could trigger, in the worst-case scenario, an outburst of four downstream lakes with a combined area exceeding 340,000$m^2$ . In the Bien basin, a number of large cascades of multiple lakes can threaten the downstream infrastructure and farmland located within 23–30 km from the potentially dangerous lakes, which is closer than in other regions. Lake Kapkan (prior to its artificial lowering) in the Khorgos basin and Lake Akkol in the Sarkand basin, are currently considered by KSAMP as the most dangerous in the region. (Kapitsa et al., 2017) provide a table (S3 table in their publication) where they describe those fifty above-mentioned lakes. (Medeu et al., 2018) (IN RUSSIAN) provide a description of mudflow hotspots in the Ulken Almaty and Kishi Almaty river basins as well as doing a repeatability study of the events. (Kapitsa et al., 2018) (IN RUSSIAN) provide a table of potentially hazardous lakes on the N slope of Ile Alatau (Table 4)

Table 4 Mudflow hazard lakes on the northern slope of the Ile Alatau

Таблица 1. Селеопасные озера северного склона Иле Алатау

| Бассейн Реки | № озера | Высота над у.м., м | Координаты | | Площадь м² | Объем (10³ м³) | Расход (Попов) м³/с | Расход (Huggel) м³/с | Потенциальные повреждения |
|---|---|---|---|---|---|---|---|---|---|
| Тургень | 13 | 3560 | 43° 7' 24,218" N | 77° 35' 5,994" E | 96 500 | 1 103 | 1246 | 2206+ | Рекреационные объекты; конеферма, сейсмостанция, водозаборы ЛЭП, дороги, мосты, водопровод |
| Тургень | 16 | 3670 | 43° 8' 28,785" N | 77° 32' 48,528" E | 66 400 | 619* | 742 | 1238+ | |
| Тургень | 15 | 3730 | 43° 8' 37,634" N | 77° 32' 21,810" E | 71 800 | 832 | 968 | 1664+ | |
| Талгар | 11 | 3400 | 43° 2' 54,401" N | 77° 11' 46,613" E | 26 500 | 150 | 208 | 300 | Кордоны, сейсмостанция |
| Талгар | 13 | 3470 | 43° 0' 31,597" N | 77° 10' 35,922" E | 67 900 | 206 | 277 | 412 | |
| Киши Алматы | 1 | 3580 | 43° 4' 43,936" N | 77° 6' 1,498" E | 20 100 | 144 | 200 | 287+ | Водозаборы, ЛЭП, дороги, мосты, водопровод |
| Улкен Алматы | 5 | 3540 | 43° 2' 21,428" N | 77° 2' 36,884" E | 37 200 | 182* | 248 | 364+ | Мосты через рр. Кумбел и Улкен Алматы, дорога ГЭС-2 – ГЭС-1, кафе, рестораны |
| Улкен Алматы | 3 | 3580 | 43° 2' 43,023" N | 77° 3' 0,989" E | 8 000 | 22 | 37 | 44 | |
| Аксай | 1 | 3530 | 43° 0' 1,643" N | 76° 49' 53,805" E | 28 600 | 166* | 229 | 333 | Село Жанатурмыс, кордон, дачи, гидротехнические сооружения, дачи, рекреационная зона |
| Каскелен | 8 | 3620 | 42° 57' 8,254" N | 76° 43' 4,076" E | 153 000 | 340 | 434 | 680+ | Кордон, дачи, д/о, жилые дома, мосты, дороги |
| Каскелен | 13 | 3740 | 42° 55' 29,867" N | 76° 44' 18,407" E | 19 200 | 143* | 200 | 286 | |
| Каскелен | 12 | 3750 | 42° 55' 37,595" N | 76° 44' 24,898" E | 17 800 | 68* | 103 | 136 | |
| Каскелен | 20 | 3450 | 42° 55' 21,950" N | 76° 36' 6,039" E | 16 300 | 73 | 109 | 145 | |
| Узун-Каргалы | 5 | 3520 | 42° 52' 59,296" N | 76° 23' 55,629" E | 45 550 | 331 | 423 | 661 | Водозаборы, ЛЭП, дороги, мосты, водопровод |
| Каргалы | 1 | 3510 | 43° 0' 23,340" N | 76° 50' 45,291" E | 4 300 | 10 | 19 | 20 | Жилые дома, водозаборы, ЛЭП, дороги, мосты, водопровод |
| Иссык | 5 | 3600 | 43° 10' 53,989" N | 77° 29' 44,233" E | 27 900 | 160* | 221 | 321 | Рекреационная зона выше озера Иссык, водозабор, гидропост, гидроузел, мосты, дороги |
| Иссык | 4 | 3640 | 43° 11' 9,608" N | 77° 30' 0,966" E | 13 500 | 55* | 85 | 110 | |



Примечание: жирным шрифтом выделены рассчитанные объемы. «*» - отмечены озера, являющиеся частью каскада. «+» указывает на возможность обрушения в озеро льда, горных пород. Включения озера № 1 в бассейне р. Каргалы, несмотря на его размеры, объясняется его частичным заполнением после прорыва в 2015 г.

(Bolch et al., 2011) provide a map with the location of potentially dangerous glacial lakes in northern Tien Shan (**Error! Reference source not found.**). In order to identify potentially dangerous glacial lakes in an automated and a most objective way, Bolch and colleagues combined the conditioning parameters (here show in **Error! Reference source not found.**) to find out which lakes are potentially of high danger and should be further investigated. Each introduced variable was tested to see if it applied to the investigated lake. If so (e.g. if a potential ice avalanche would reach a lake), a value of one (1) is assigned to the lake; otherwise a zero (0). Their workflow was: Identification of variables→ordering variables according to importance→assigning weighing factor to each variable→check if variable applies for lake→multiplication and summarizing of variables→classification of lakes according to potential danger (see (Bolch et al., 2011)).

- **Future hazard and risk**

(Kapitsa et al., 2017) identified fifty lakes whose potential outburst can damage existing infrastructure were identified in the Zhetysu Alatau region, mainly in the NW ansd SW sectors (basins of rivers Usek, Khorgos, Sarkand, Tentek, Asku, Bien, Kora, Koktal and Lepsy). The three largest lakes had individual areas of about 200,000 m$^2$ . The potential worst-case scenario peak discharge of the three largest lakes was estimated to exceed 5600m$^3$/s. Peak discharge of 35 lakes may exceed 300 m$^3$/s$^-$, which was the registered velocity of the flow that devastated the town of Sarkand in 1982 following the outburst of Lake Akkol (N 43) positioned 45 km upstream (Tikhomirov and Shevyrtalov, 1985). The characteristic arrangement of lakes in vertical sequences or cascades creates the potential for outburst of multiple lakes. Therefore, even small lakes (e.g. six lakes with areas below 20,000 m$^2$), which are frequently disregarded in GLOF assessments, may be hazardous. A total of 513 overdeepenings with individual areas of more than 11 000 m$^2$ were detected in the modelled glacier beds within the glacierized area in the year 2000. Their combined area was estimated as 14.7 km$^2$, which corresponds to 3% of the total glacierized area. Most overdeepenings are small and shallow with length and width of a few hundred meters and maximum depth of 65m. Larger overdeepenings with individual areas between 0.05 and 0.5 km$^2$ are found in the regions where existing lakes are most abundant (the Aksu, Usek and Khorgos basins), but also in the NE of the region where the existing lakes are small and currently less numerous, but where new lakes develop and the existing ones show rapid (over 100 %) increase (see table S3 in (Kapitsa et al., 2017)). Future research will focus on the significance of the hazard potential of these lakes through further investigation of lake dams and surrounding slopes using high-resolution remote sensing and field studies and physically based flow models. The observed and modeled evolution of the lakes should be regularly reassessed against each other and against changes in land use and infrastructure to inform hazard management and planning.

(Kapitsa et al., 2018) identified 154 glacial lakes have been identified on the N slope of Ile Alatau, with a total area of 2.28 $km^2$. 17 of these lakes located between 3400 and 3750 m are are found to present a high degree of mudflow hazard. In the face of ongoing climate warming and intense degradation of glaciers, the destruction of dams is at high risk and hence the formation of destructive mudflows. Thus, the need to continue monitoring the state of glacial lakes on a permanent basis based on preventive measures to reduce the volume of water in lakes to reduce the risk of glacial mudflow formation.

(Narama, et al., 2009): Large cities such as Almaty have developed on alluvial fans at the bases of outer ranges. These urban centers rely on glacier meltwater for domestic water, irrigation, industry, and hydropower (Severskiy et al., 2006; UNEP, 2007) and water use has increased in both urban and rural areas of the outer Tien Shan range (Oosinova, 2001). As urban populations are foreseen to increase over the coming decades, and declining water discharge leads to depleted groundwater reservoirs, cities along the outer ranges of the Tien Shan may experience enhanced problems for water supply. Other problems associated with glacier shrinkage are glacier hazards such as glacier lake outburst floods (GLOFs). Glacier lakes have developed rapidly since the 1970 s in the outer ranges of the Tien Shan. Recently developed pro-glacier lakes have reached sizes similar to lakes found in the 1960 s–1970 s, when a number of catastrophic GLOFs occurred (e.g., Kubrushko and Staviskiy, 1978; Baimoldaev and Vinohodov, 2007; Narama et al., 2009). Lake outbursts may thus become an increasing threat in the Tien Shan. The above factors stress the need for research on sustainable water-use practices and monitoring of glacier change and glacier-related hazards.

- **Risk management and response**

In August 2014, periodic artificial lowering of Lake Kapkan commenced in the Zhetysu Alatau to prevent its outburst (Kapitsa et al., 2017).

(Stepanov & Yafyazova, 2016) (IN RUSSIAN) review the preventive emptying measures at lake No13-bis on the Sovetov glacier (Kumbel river basin - N slope of Ile-Alatau) which can threaten the city of Almaty, and provide recommendations for optimizing future work. They also review the emptying in 2010 of a lake formed over the Zoya Kosmodemyana glacier in the same river basin; as well as the mudflow during the emptying of lake No.13 in 1977. The authors recommend doing an additional drainage channel in the NW part of lake No.13-bis.

(Medeu et al., 2020): To protect against mudflows in the valleys of the Ile Alatau, 14 dams have been built and two more are planned. To prevent outbursts of moraine lakes, they are emptied using pumps and siphons. In 2019, the network of automated monitoring of early warning about mudflows is being organized, which will cover all the valleys of the Northern slope of the Ile Alatau.

(Kapitsa et al., 2017) consider that the GlabTop2 approach is a useful hazard management tool as it provides information on the potential evolution of future lakes. The use of the most stringent criteria derived from the previous GLOF events, literature and empirical models (e.g. peak discharge resulting from the worst-case scenarios) implies that anticipated floods are low probability events, and further justification through physical modeling of floods and mudflows and field surveys, focusing on the state of lake dams, is required. An example, where further modeling of potential floods is needed to constrain uncertainty and assist planning, is the basin of the Bien River, where a rapid increase in newly formed lakes is observed, comparatively close to the existing infrastructure, and their further increase is projected to potentially result in the formation of one of the largest lakes in the region. In August 2014, periodic artificial lowering of Lake Kapkan commenced in the Zhetysu Alatau to prevent its outburst (Kapitsa et al., 2017).

(Kapitsa et al., 2018) (IN RUSSIAN) provide bathimetry information on Lakes Akkol, No. 13 (Turgen river basin), lake under Mametova glacier, Lake No. 15 (Ulken Almaty river basin) as well as information on works done on the lake under Mametova glacier in 2017. Despite the preventive measures taken by Kazselezhechita to reduce the level of lakes in the basins of the Kishi Almaty (under the Mametova glacier) and Ulken Almaty (under the glacier Soviets), the volume in the lakes is still significant and in the event of a breakthrough mudflows can form with a flow rate hundreds of times higher than the average for ablation period. As a result of the measures taken on the lake under the Mametova glacier in the river basin Kishi Almaty the volume of water mass was reduced from 241 thousand $m^3$ in 2010 to 143 thousand $m^3$ in 2017.

An article for the reliefweb news and press release after the july 23rd 2015 mudflow event on Almaty describe that Almaty city is protected from mud flows by three dams installed on the Malaya Almatinka, Bolshaya Almatinka and Kargalinka rivers and according to Dr Boris Stepanov, all of them were in a good condition in 2015. A problem that was signaled by Dr. Stepanov was that all three dams are only capable of withstanding one mud stream and there was no backup plan in case the mud storage reservoir becomes full. Such storage poses the greatest danger for the city, as if the dam fails, it could lead to tragic consequences for Alamty and it's residents. According to the professor, Almaty is still in danger, because there are other moraine lakes, which could burst so he suggests draining the lakes. Currently, Kazselezaschita (the mud flow protection service) uses a siphoning method to discharge extra amounts of water to avoid overflowing of the lake. But it is possible to lower the water level by only around 5 m at a time. In addition, a lake can burst in its underground, as it happened in 2015. Following the incident, the city's Mayor in 2015 Akhmetzhan Yessimov stressed the necessity to build new mud flow protection facilities on the Aksai and Kumbel rivers as well as to strengthen the Mynzhylky dam located 4 km away from Shimbulak skiing resort. In addition, he instructed to conduct a study to gather information on the changes in the glaciers and moraine lakes due to the abnormal weather conditions.

(Medeu, 2011) (IN RUSSIAN) in his book provide scientific and applied aspects of the management of mudflow processes. Mudflow-preventive constructions are considered for the protection of the population as well as social and economic objects. The book is intended for geographers, engineers-geologists, designing firms. It includes pictures of past mudflow events, diverse schemes of mudflow deposits, types of dams, etc, bathymetric maps, description on triggering factors for mudflow formation, examples and pictures of preventive structures.

(Medeu et al., 2020) (IN RUSSIAN) describe the system of mudflow response measures in Ile Alatau. The management and response system includes: (a) assessment and mapping of mudflow hazard and mudflow risk, (b) preventive emptying of moraine lakes, (c) monitoring and early warning systems for mudflow hazard, (d) construction of mudflow protection dams. (a) The mudflow hazard maps show the borders of mudflows with different intensity and frequency. Mudflow risk maps were compiled separately for social, economic and environmental risks. Maps based on the results of the average annual damage from mudflows show areas with low, moderate and high-risk levels. (b) Preventive emptying of lakes has been carried out since 1964. Since then empting has been done on more than 20 lakes. In recent years, seven moraine lakes have been regularly emptied by surface runoff channels and pumping water with pumps and siphons. (c) Monitoring and early warning of mudflows includes: 30 automatic monitoring stations (8 stations on moraine lakes, 6 stations in mudflow formation sites, 9 stations in mudflow channels, 5 stations on mudflow dams), and two control centers, one of them in the Department of Emergency Situations of Almaty. The monitoring network was planned to be completed during the year 2020. (d) 14 dams were built and 2 new dams are planned. In two mudflow channels, cable-mesh barriers are installed.

The emptying of moraine lakes is the main preventive measure to reduce damage from breakthrough glacial mudflows in Kazakhstan. The economic efficiency of preventive work is quite high. The cost of preventive work is less than the cost of delaying mudflows and eliminating the consequences of mudflows. The emptying of lakes is included in the general complex of anti-mudflow measures to prevent an uncontrolled outburst of a moraine lake.

Moraine lakes can represent a real and potential threat of a lake outburst with the formation of a catastrophic mudflow. In this regard, emptying the lake to safe levels, with the organization of a discharge channel, is the only solution that will eliminate the threat of a catastrophic outburst of the lake and the formation of a mudflow.

Preventive measures carried out at different times and on different lakes show their effectiveness. Examples are the emptying of moraine lakes in the basins of the rivers of the Ile Alatau ridges (Shelek, Ulken and Kishi Almaty, Talgar rivers), and the Zhetysu Alatau ridge (Korgas, Osek, Aksu, Sarykan etc. rivers).

Preventive measures are developed based on an analysis of the situation based on the results of surveys, including commission fees, hydrometeorological conditions, and a generalization of all available materials.

In Kazakhstan, the issues of emptying lakes began to be dealt with in the 60s of the twentieth century. Currently, when emptying moraine lakes, various emptying methods are used, including the installation of polyethylene pipe threads of various diameters, the installation of various water pumps, using small and heavy construction equipment and manual labor, drilling and blasting, and others.

For the entire period of activity of the GU "Kazselezashchita" preventive work was carried out to empty more than 50 moraine lakes in 15 basins of the Ile and Zhetysu Alatau river ridges.


Works on the expansion and deepening of evacuation channels on moraine lakes are carried out using drilling and blasting.


Also, the work is carried out manually and using special heavy construction equipment.


Water is discharged from the lake by installing siphon threads. Optimum are plastic pipes for siphons, with diameters of 200-300 mm and a wall thickness of more than 10 mm.


Lake emptying using a water pump

Explosion of a bridge on Lake No. 13 in the upper reaches of the Kumbelsu, a tributary of the Ulken Almaty River (1977)

## *ANNEX*

**Table A1:** historical debris flows in Ile Alatau from (Medeu et al., 2019), and (Bolch et al., 2011)

| Date | Location | Trigger | Discharge and Transported Volumes ($m^3$) and Flow Rates ($m^3/s$) | Losses and fatalities | Preventive works and infrastructure |
|---|---|---|---|---|---|
| 1841 | Many rivers | | | High human losses | |
| July 8-9, 1921 Varnyi (Almaty) debris flow catastrophe | Kishi Almaty River | Heavy rain: >70 mm | transported material : >2 M $m^3$ | Human losses > 500 in Vernyi Town (Almaty) | - |
| July 8, 1950 | Ulken Almaty River basin | Heavy rain: 60 mm/h | | Water intake of the HEP cascade, settlement, 10 km of road, electric power line, livestock and human losses | - |
| August 20, 1951 | Kishi Almaty River basin | Outburst of glacial lake Nr. 2, near Tuiyksu glacier | Transported: 20 thou $m^3$ flow rate: 30 m3/s | Bridges in the Kishi Almaty River | - |
| August 7, 1956 | Kishi Almaty River basin | Outburst of glacial lake Nr. 2, near Tuiyksu glacier | 1.1M $m^3$ flow rate up to 1000 $m^3/s$ | Serious destruction and human losses | - |
| July 7, 1963 | Esik River basin | Glacial lake No. 17 outburst near the Zharsai (right) glacier, which led to a subsequent outburst of downstream Esik Lake. | 5.8 M $m^3$ flow rate up to 12tho $m^3/s$; | serious destruction. A large number of people recreating on the lake shore were killed | - |
| July 15, 1973 | Kishi Almaty River basin | Outburst of glacial lake No. 2 near Tuiyksu glacier | Glacier lake outburst volume: volume: >200 x $10^3$ $m^3$. Maximum discharge at the lake outburst: 250-280 $m^3/s$; Max. debris flow discharge - >10,000 $m^3/s$; transported volume: 3.8 x $10^6$ $m^3$. | | in 1966 started the construction of a dike at Kishi Almaty basin. construction completed in 1972. in 1973 it saved the city from destruction. Medeu debris flow storage was filled nearly to the top but dam survived. Later, its height was increased, and the debris flow storage capacity was 12.6 M $m^3$. It intercepted 3 debris flows similar to the 1973. |

| | | | | | |
|---|---|---|---|---|---|
| August 3, 1977 (and 9 other subsequent debris flows). | Khumbel river basin (right inflow of Ulken Almaty valley) | Glacial lake No. 13 outburst near Sovetov glacier. | Volume of outburst flood: 80 x $10^3$ $m^{3.}$ Max. outburst discharge: 210 $m^3$/s. Maximum debris flow discharge: 11 x $10^3$ $m^3$/s. Transported volume: 4.24 x $10^6$ $m^3$. | Destroyed bridges and the Almaty–Kosmostantsiya, electric power line and water supply line; the hydraulic structures of the HEP cascade were damaged. Human losses were recorded. a deposit-water flood was left at the city of Almaty. the sides of the debris flow channel collapsed after this passage where 9 further debris flows took place in August. | - |
| June 21, 1979 | Middle Talgar River basin | Glacial lake No. 7 near Sportivnyi glacier | Volume of outburst flood 82,000 m3; maximum outburst discharge 15 m3/s; transported volume – 113,000 m3. | | - |
| July 23, 1980 | Kaskelen River basin | Glacial lake No. 16 near glacier No. 25. | Outburst flood volume – 100,000 m3; maximum debris flow discharge 2,000 m3/s; transported volume: 2,0 M m3 | | - |
| July 6, 1993 | Talgar River basin | Glacial lake No. 8 outburst near Bezymyannyi glacier | Outburst flood volume: 100,000 m3; maximum debris flow discharge 2,000 m3/s; transported volume: 2,0 M m3 | damaged roads, water supply line and the electric power line. | - |
| July 14, 1999 | Left tributary of the Kishi Almaty (Bedelbai Brook) | heavy rain: 106 mm→mudflow | Max. flow rate: 200 $m^3$/s Transported volume: 30 thou $m^3$ | destroyed the bridges, the Almaty–Medeu road, the water supply line, the gas pipeline and the electric power line. | |
| July 6, 2006 | Kumbelsu River, right tributary of Ulken Almaty River | Heavy rain: 51 mm | Max. debris flow rate: 800 $m^3$/s. Transported volume: 1 M $m^3$ | debris flow destroyed bridges and Almaty – Kosmostantsiya road. Fifty people blocked in the gorge, rescued by helicopter. | |
| July 17, 2014 | Middle Talgar River basin | Glacier lake outburst near Solnechnyi glacier | volume of deposits in front of dam: 300 thou $m^3$ | debris flow entered channel of Middle Talgar and reached protective dam. damaged several houses, the road and the electric power line. | Debris flow protective dam |
| July 23, 2015 | Kargaly River | subglacialoutburst of lake under the Kargalinskii glacier | volume of lake: 325 thou m3. Transported volume 260 thou m3. reached the protective dam and stored about 50 thou $m^3$ of loose debris material, with about 100 | damaged residential buildings, road and electric power line. More than a thousand people had to be rescued. The liquidation of the consequences required more than $ 10 million. | Debris flow protective construction (dam) |

| | | | | | |
|---|---|---|---|---|---|
| | | | thou $m^3$ of water which was discharged with a max. flow rate of 30 $m^3/s$, and gave a $2^{nd}$ debris flow | | |

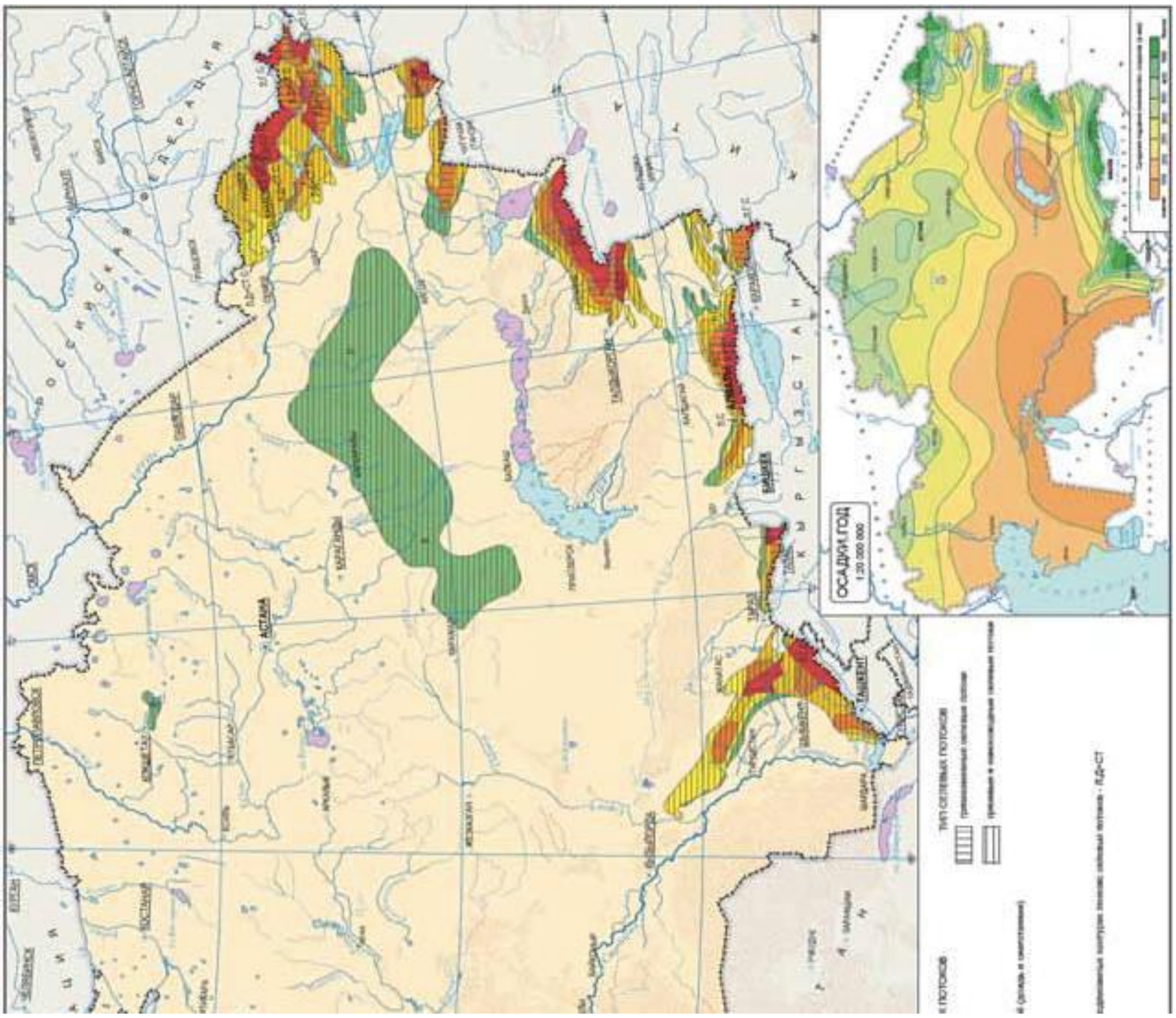
Mudflow in Esik (Ile Alatau) 1963 (Medeu, 2015)

Mudflow in the Ulken Almaty River basin (Ile Alatau) 2006 (Medeu, 2015)

Video wall with automated monitoring stations in the situation room of the Department of Emergency Situations of Almaty (Medeu et al., 2020)

Pump mounted on a floating platform (A. P. Medeu et al., 2020)

stopping reinforced concrete grid dam on the Kaskelen river (A. P. Medeu et al., 2020)



Part of the map of mudflow areas in Kazakhstan (from the “Atlas of natural and man-made hazards and risks of emergency situations” Almaty, 2021. Occurrence of mudflows increase from green to red. (Medeu, 2015)

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