GLOFCA PROJECT
«Reducing vulnerabilities of populations in the Central Asia region from glacier lake outburst floods in a changing climate»

Report on task 9A part 1:
study of the peculiarities of the development of outburst-prone lakes on moraine-glacial complexes of the Ala-Archa River valley (research is conducted on the basis of the high-mountain glaciological station Adygene)

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Content

Introduction 3

1. Genesis and shape of moraine-glacial complexes 4

2. Types of moraine-glacial complexes 5

2.1. Third type of moraine-glacial complexes 6

2.2. Moraine-glacial complexes of the fourth type 6

2.3. Fifth type of moraine-glacial complexes 7

3. Peculiarities of formation of outburst prone lakes on different types of moraine-glacial complexes 8

3.1. Conditions for the formation of a lake of the intramoraine depression subtype 8

3.2. Conditions for the formation of a lake of the nieche glacier depression subtype 10

3.3. Conditions for the formation of lakes of the thermokarst sinkhole subtype 13

Conclusion 14

Introduction

Outbursts of mountain lakes are a common phenomenon in mountainous regions. From 1953 to 2023, 85 cases of hazardous mountain lake outbursts have been recorded in Kyrgyzstan. On average, this equates to 1.2 outbursts per year. Among these, 15 outbursts, or 17.6%, occurred in the valley of the Ala-Archa River. In six instances, outburst floods transformed into powerful debris flows, with discharge rates reaching several hundred cubic meters per second, leading to catastrophic consequences for the residents of the Ala-Archa River valley and Bishkek city. Therefore, the Ala-Archa River valley is considered one of the most mudflow hazard-prone valleys in the Northern Tien-Shan region.

All outburst prone lakes in the Ala-Archa River valley, those that have previously experienced outbursts and those actively developing at present, are of the moraine-glacial lake type.

In the history of mountain lake studies, the phenomenon of moraine-glacial lake outburst was underestimated. Just a few decades ago, this occurrence was considered quite rare and more of an exception. In the 1950s, only outbursts of dam-formed lakes were considered dangerous, while scientists viewed glacial and moraine-glacial lakes as beautiful, unique elements of high-altitude landscapes, typically thought to be of insignificant size and posing no significant threat to the valleys below. Therefore, on the map of mudflow hazard of the USSR, issued in 1974 (edited by S.M. Fleishman), the region of the Northern Tien-Shan is referred to the zone of torrential mudflow formation (Fleishman, 1978). But after a series of catastrophes caused by outbursts of moraine-glacial lakes, the assessment of their hazard shifted toward recognizing their catastrophic potential. This is due, first of all, to the ability of an outburst flow to increase its discharge many times, tens of times, when transformed into a debris flow. Therefore, the mudflow specialists of Kazakhstan even proposed to consider outbursts of moraine-glacial lakes as a special geological phenomenon, different from the usual debris flow-forming process (Bizhanov, 1998).

Over the past 65 years, the number of moraine-glacial lakes has significantly increased due to the climate change and glacier degradation. For example, in the period from 1977 to 2023, 17 new moraine-glacial lakes appeared after glacier retreat on the Adygene moraine-glacial complex in the Ala-Archa River basin. Among them, 3 lakes of the subtype of intramoraine depressions: 2D, 4D and 5D, one lake of 6D subtype of niche glacier depression and 13 lakes of thermokarst subtype (Fig. 1).

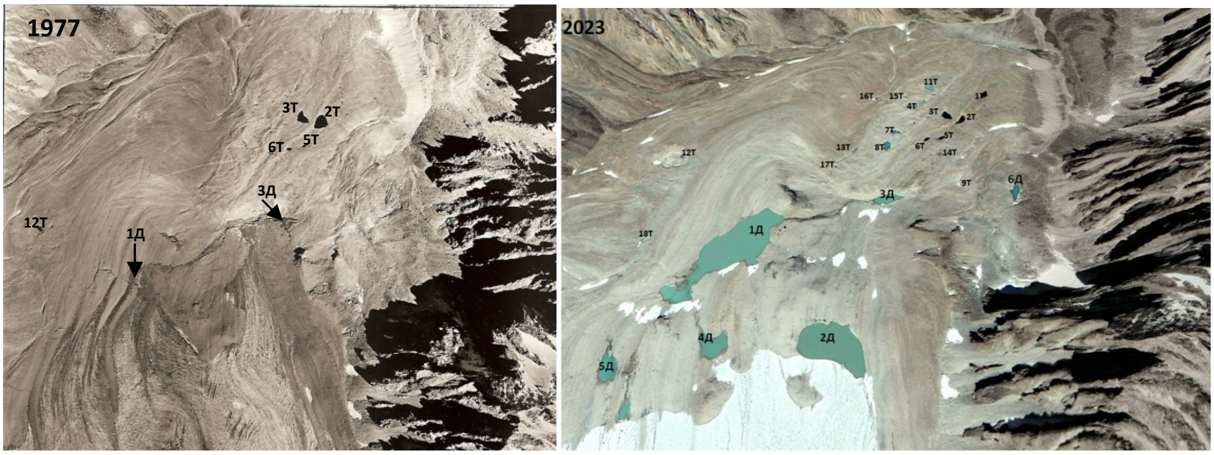

Figure 1. The section of the Adygene moraine-glacial complex, where 17 new moraine-glacial lakes have appeared over the last 46 years. Among them, 3 lakes of the subtype of intramoraine depressions: 2D, 4D and 5D, one lake of 6D subtype of niche glacier depression and 13 lakes of the thermokarst subtype.

Moraine-glacial lakes are lakes of a special type, the base or foundation for the formation of their basins is moraine-glacial complexes, and the main source of accumulation is the melt water of glaciers and buried ice.

1. Genesis and shape of moraine-glacial complexes

A moraine-glacial complex is a geological body formed by a glacier during the last glacial epoch, "within a specific physiographic setting and composed of a particular set of facies that shape its internal structure". This geological body comprises various formations of glacial lithogenesis: boulders of relatively pure ice detached from the glacier (referred to as buried ice), moraine-containing ice, and ice-containing moraine, coarse material of an ablation moraine, fluvioglacial and limnoglacial deposits.

Moraine-glacial complexes are complex geological formations of degrading mountain-valley glaciers. The process of formation of moraine-glacial complexes of modern glaciers began in the Little Ice Age (in the period of the 13th - 19th centuries) and continues at present. These complexes consist of the following primary morphological elements: 1) frontal and lateral moraine ridges, 2) intra-moraine depressions, and 3) terminal moraine tongues transitioning into gletcher tongues.

Each glacier forms its own moraine-glacial complex, the shape, composition, and structure of which depend on the glacier's capacity for moraine formation. This capability is determined by the action of two factors in glacial lithogenesis. The first factor characterizes the glacier's content of debris material and its ability to accumulate this material in its terminal zone, known as the moraine-forming zone. The first factor is the accumulation factor - A. The second factor involves the erosive power of meltwater streams flowing from the glacier and their ability to erode accumulations of debris material in the glacier's terminal part, within the moraine-forming zone. This factor is erosion or ablation - E. The shape, composition, and structure of moraine-glacial complexes depend on the balance between these factors.

2. Types of moraine-glacial complexes

There are glaciers where the effect of factor E is maximized, while factor A is suppressed. These are glaciers, such as Aksai and Golubin, where the moraine-glacial complex is almost completely eroded by meltwater flows (Fig. 2). On these glaciers, the process of moraine formation is at the initial stage. On the other hand, there are glaciers whose degradation has gone so far that factor A suppresses factor E, which causes the formation of powerful terminal moraine tongues, within the moraine-glacial complex, as seen in Adygene (see figure 3).

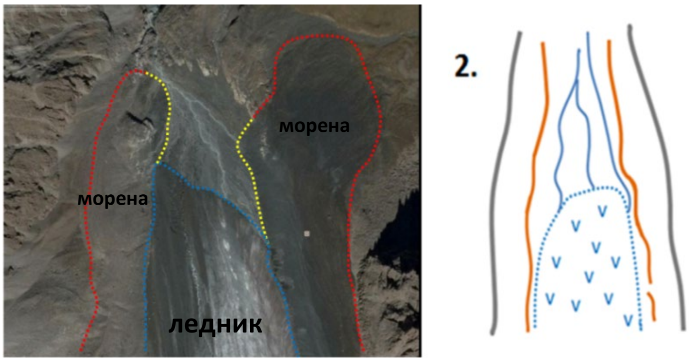

Fig.2. Moraine-glacial complex of the 2nd type with a fluvioglacial zandra field open down the valley between the ridges of lateral moraines.
Northern slope of the Kyrgyz ridge, Golubina glacier
Legend in Fig. 6

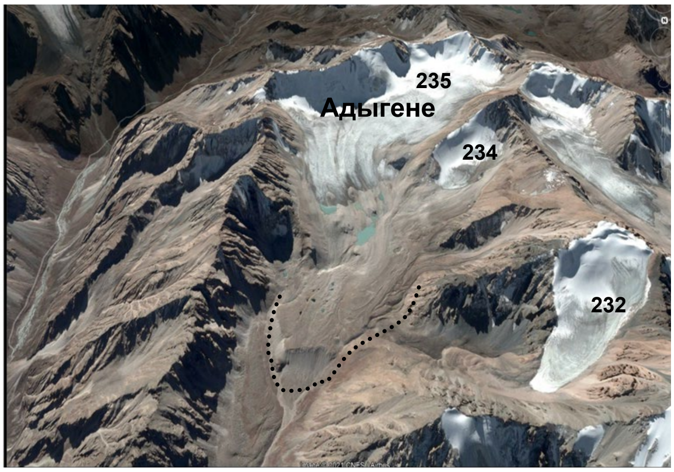

Fig.3. Moraine-glacial complex of the Adygene glacier is represented by a powerful terminal moraine tongue.
232- glacier numbers in the catalog

Between glaciers in the initial and terminal stages of moraine formation, there are glaciers in intermediate stages with distinct, unique intermediate types of moraine-glacial complexes in terms of their composition and structure. During the process of moraine formation, glaciers create six types of moraine-glacial complexes, with a complete or partial set of the following morphological elements: 1) frontal and lateral moraine ridges, 2) intra-moraine depressions, 3) terminal moraine tongues transitioning into gletcher tongues.

Not every moraine-glacial complex can develop a lake on its surface. For this, it's necessary to have specific conditions and a particular shape, composition, and structure. The most favorable conditions for forming lake basins are found within the 3rd, 4th, and 5th types of moraine-glacial complexes, which include enclosed or semi-enclosed intra-moraine depressions, niche glacier depressions, and terminal moraine tongues.

2.1. The third type of moraine-glacial complexes comprises frontal moraine formations alongside shore moraine ridges, in the form of one or several terminal moraine ridges overlapping each other. Behind this ridge, between the lateral moraine ridges, an intra-moraine depression forms (see figure 4). The erosive power of meltwater streams on glaciers forming the third type of moraine-glacial complexes is significant enough to create a breach or channel within the frontal moraine ridge. Hence, the intra-moraine depression in moraine-glacial complexes of the third type is open through a breach downward into the valley. Within such intra-moraine depressions, basins of moraine-glacial lakes form, with surface runoff. For instance, the intra-moraine depression filled with water in Lake Bolshoye Adygene on the surface of the Adygene glacier's moraine-glacial complex (see figure 4).

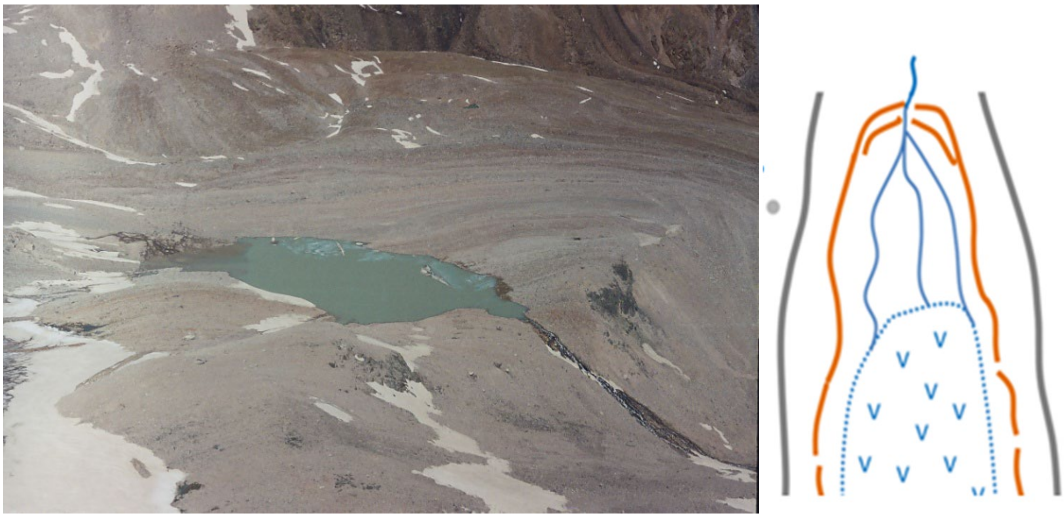

Fig.4. The open intramoraine depression of the moraine-glacial complex of the Adygene glacier is filled with water from Lake Bolshoye Adygene
Legend in Fig. 6

2.2. Moraine-glacial complexes of the fourth type develop on glaciers where the erosive power of meltwater streams is no longer sufficient to create a breach in the frontal moraine ridge. That is why, the intra-moraine depression in these complexes is entirely closed. At the bottoms of such depressions, lakes with underground flow are usually formed, representing the most hazardous outburst prone among moraine-glacial lakes. The frontal moraine in fourth-type complexes is characterized by one or several terminal moraine ridges, which, overlapping each other, create a terminal moraine tongue, which is most developed on moraine-glacial complexes of the 5th and 6th types.

An example of type 4 complexes in the Ala-Archa River valley is the moraine-glacial complex of the Teztor Glacier, with an extensive intramoraine depression periodically filled with water from Lake Teztor (Fig. 5).

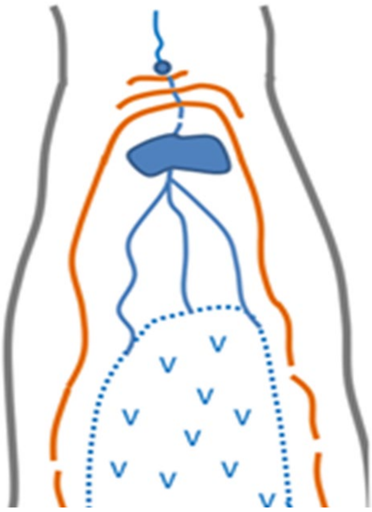

Fig. 5. Fourth-type moraine-glacial complex of the Teztor Glacier with a closed intra-moraine depression, periodically filled with water of Lake Teztor.

Legend for Figure 6.

2.3. Moraine-glacial complexes of the fifth type form under conditions where the volume of debris material entering the glacier's terminal part exceeds the erosive capacity, that this results in the merging of shore and frontal moraines into a single terminal moraine tongue, which is due to a high concentration of buried ice within it, moves autonomously downhill along the valley. The terminal moraine tongue consists of a series of overlapping frontal moraine ridges and extrusion moraine ridges. Between the terminal moraine tongue and the glacier tongue, a closed intra-moraine depression forms, in which a lake is formed, such as Lake Kashkasu on the glacier of the same name (see figure 6). Such lakes, with underground flow, can become highly hazardous at a certain stage of development due to an underground mechanism of outburst.

5.

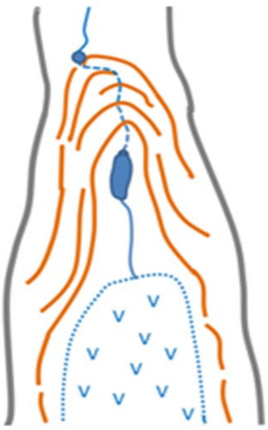

Figure 6. The terminal moraine tongue is the primary characteristic of fifth-type terminal moraine complexes. Kashkasu Glacier on the northern slope of the Kyrgyz Ridge in the Ala-Archa Valley

Условные обозначения к рисункам 3-6

На фото

Границы: - моренно-ледникового комплекса и валов конечных морен;

- внутриморенной депрессии;

- языка ледника.

На схемах

- борта долины; - валы конечных морен, боковых и фронтальных;

- граница ледника; - русло водоток;

- озеро; - подземный канал стока

3. Peculiarities of formation of outburst prone lakes on different types of moraine-glacial complexes

In the depressions of moraine-glacial complexes of the 3rd and 4th types, lakes of the intra-moraine depression subtype form. Within fourth-type moraine-glacial complexes, lakes of the niche glacier depression subtype are formed. On the terminal moraine tongues and, less frequently, the terminal moraine ridges of fourth and fifth-type moraine-glacial complexes, lakes of the third subtype, thermokarst sinkholes, develop.

3.1. Conditions for the formation of a lake of the intramoraine depression subtype

When a glacier retreats, its marginal parts are armored by thawing debris material and manifest on the surface as terminal moraine ridges. The central part of the glacier lacks such a quantity of debris material and melts considerably deeper than the marginal parts.

Therefore, after its degradation, an intramoraine depression is formed in the center of the glacier, into which glacier meltwater flows. If the depression is open through a gap in the body of the frontal moraine ridge, the water in the depression flows downward through the valley without being retained (see figure 7). If, however, it is entirely blocked by the frontal ridge, the drainage of meltwater from the depression through water-impermeable moraine-glacial deposits is significantly impeded, leading to the accumulation of meltwater in the depression (see figure 8). Under the influence of solar heat, it warms up to a temperature of 7-10°C and actively affects its bottom and sides, composed of moraine-containing ice and ice-containing moraine. The heated meltwater, through the action of thermokarst processes, creates a basin for itself. The water volume in such lake basins in the Ala-Archa river valley can reach 50-80 thousand m^3.

Fig.7. Lake Topkaragay was formed in an open-type intramoraine depression on the moraine-glacial complex of the same name in the upper reaches of the valley of the Top-Karagay River, a left side tributary of the Ala-Archa River. After an outburst in 1993, the lake has surface runoff

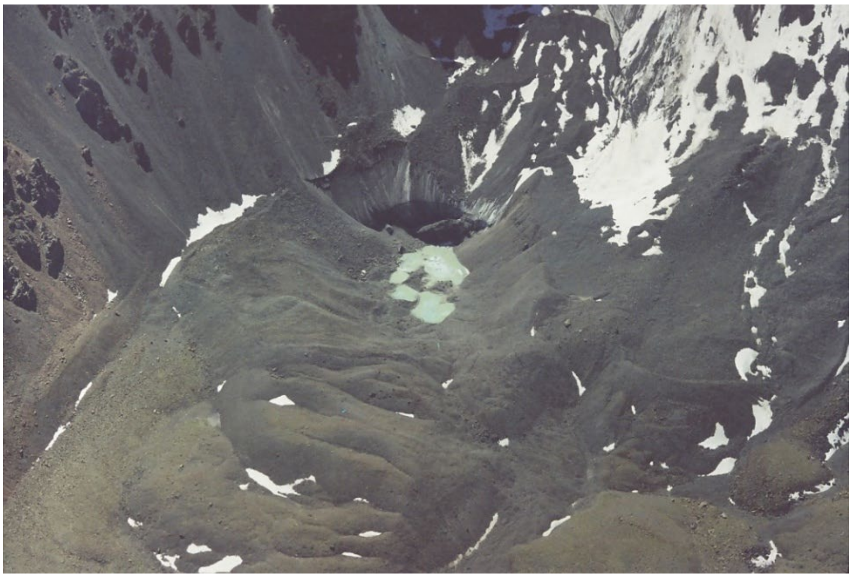

Fig.8. Lake Kashkasu formed in a closed intramoraine depression of the moraine-glacial complex of the Kashkasu Glacier, in the upper reaches of the Kashkasu River valley, a left side tributary of the Ala-Archa River

The action of thermokarst processes is directed not only at expanding the basins of moraine-glacial type lakes, but also at formation of underground drainage channels within the dam structure (see figure 9), through which underground lake outbursts occur, often resulting in catastrophic consequences for residents in the lower valleys.

Fig. 9. Entrance hole to the underground intra-marine drainage channel, through which Teztor Lake breached in 2004

3.2. Conditions for the formation of a lake of the niche glacier depression subtype. Последние 15лет результаты изучения прорыоопасных озер привели к необходимости выделения еще одного подтипа моренно-ледниковых озер, а именно озер присклоновых моренных депрессии. В отличие от внутриморенных депрессий, которые образуются, как элемент моренно-ледниковых комплексов долинных ледников, присклоновые моренные депрессии проявляютсякак элемент моренно-ледниковых комплексов присклоновых ледников, после их деградации (рис.10).

Over the last 15 years, the results of studies of outburst prone lakes have led to the necessity to distinguishing another subtype of moraine-glacial lakes, namely, lakes of niche glacier moraine depressions. In contrast to intramoraine depressions, which are formed as an element of moraine-glacial complexes of valley glaciers, niche glacier moraine-glacial depressions appear as an element of moraine-glacial complexes of niche glaciers after their degradation (Fig. 10).

Fig. 10. Upper reaches of the Adygen valley. The niche glacier intramoraine depression is filled with water from the lake of glacier № 234, descending down the slope from the

northern exposure of the peak "40 years of VLKSM". The lake breach occurred in 2010 with a gradual release of water

Formation of niche glacier depressions is closely linked to avalanches, whereby substantial masses of snow accumulate at the base of the slope, transforming into ice during the development of a niche glacier. At the base of the slope, the ice thickness will be maximal since it accumulates the largest amount of snow carried by avalanches.

Loose clastic material carried down from the slope by avalanches is squeezed out to the periphery of the slope glacier, and pure ice accumulates at the foot of the slope. Therefore, during degradation of the niche glacier, the clear ice at the foot of the slope thaws much deeper than the peripheral parts of the glacier, as it does not have enough loose clastic material to form a thermoprotective cover. The possibility of forming such a cover exists in the peripheral parts of the slope glacier, so here, after its melting, a terminal moraine ridge is formed, arcing around the most deeply thawed part of the niche glacier - the niche moraine depression. Lake Adygene D-6 (Fig. 11) was formed in such a niche glacier depression at the foot of the glacial slope of northwestern exposure, descending from the Shubin peak. In August 2023 the volume of the lake was about 30 thousand m^3. The lake is at the outburst hazardous stage of development.

Fig.11. Lake Adygene D-6 formed at the foot of the niche glacial depression of northwestern exposure descending from Shubin peak

During the process of glacier degradation, niche glaciers transform into slope glaciers. Meltwater running off the glacier slope accumulates at the base of the niche glacier moraine depression because its further movement down the valley is hindered by water-impermeable deposits of ice-containing moraine, forming the sides and bottom of the slope depression. The volume of accumulated meltwater can reach 100,000 m^3. The water is heated by solar warmth to 8-12°C and affects the slopes and bottom of the niche glacier depression, forming the lake basin. The formation activity depends on the rate of formation of the thermal protective layer along the sides and bottom of the lake basin. In the process of its development thermokarst processes can destroy the already formed thermal protection layer, especially in the areas of intraglacial channels. In this case, the channel may open and lake outburst may occur through it, as it happened with the lake near Glacier № 234 on July 10, 2010 (Fig.12).

Fig.12. A gaping cavity at the entrance to the underground intramoraine drainage channel, through which the breach of Lake № 234 occurred in 2010.

The outburst flow rate depends on the drainage channel's capacity, determined not only by its cross-section at the narrowest points but also by its length, the nature of its bends, and their quantity. The extension of an intraglacial flow channel through a moraine-glacial complex can be quite bizarre. For example, the intraglacial drainage channel through which the outburst of glacier lake № 234 occurred diagonally intersected the moraine-glacial complex Adygene from the right side to the left. Steep bends and numerous minor bends hindered the increase in the speed of the outburst flow within the drainage channel, thereby reducing its flow rate. Therefore, the flow rate of the outburst flow during the breach of this lake was only 3-4 m^3/sec, preventing its transformation into a debris flow.

Lakes in niche glacier depressions have several distinct features compared to lakes in intramoraine depressions:

1) Drainage from these lakes is only underground, through intraglacial drainage channels.
2) Breaches of these lakes occur only through one option—underground channels.

3) Inflow into these lakes has a downward trend due to the active degradation of slope glaciers.

Similarly to lakes in intramoraine depressions, lakes in niche glacier moraine depressions can have a non-stationary development regime, where their filling depends on the capacity of the underground intramoraine drainage channels.

One of the most typical non-stationary lakes of this subtype is Lake Teztor-2 in the Ala-Archa River basin on the northern slope of the Kyrgyz Ridge (Fig. 13). This lake has filled and breached three times in the last 20 years: in 2004, 2012, and 2018. Only in 2012 the outburst flow transformed into a debris flow, frightened the residents of the Ala-Archa river valley and Bishkek. In 2004 and 2018, the draining of the lake occurred without significant consequences for the lower valleys of Adygene and Ala-Archa.

Fig. 13. niche glacier Lake Teztor-2 (Ch-8) before the breach on July 31, 2012.

The example of Lake Teztor provides an important conclusion that characterizes the features of niche glacier moraine depression lakes: an increasing volume indicates the rising risk of a niche glacier lake breach, as the filling period of its basin culminates in a breach, releasing a part or the entire volume of the lake.

3.3. Conditions for the formation of lakes of the thermokarst sinkhole subtype

The basins of thermokarst sinkhole lakes form on the ridges of terminal moraine, their sides, frontal areas, and on the surface of glacier terminus. Their number in large terminal moraine complexes, like the Adygene complex, can reach several dozen (see figure 1).

Thermokarst lakes appear in areas where buried ice melts. mechanism of their formation has so far been poorly studied. Most likely, they are the result of thermokarst processes in the areas of re-veined or cracked ice. Thermokarst sinkholes where water accumulates have typically a rounded, often elliptical shape in plan (see figure 14). Their diameter can reach 50-100 meters, and depth from 1-2 to several meters. Water in sinkholes accumulates due to melting of ice that composes the bottoms and sides of sinkholes, melting of snow falling into sinkholes. It is also possible for melt water to run off from the moraine-glacial slopes of the sides of the sinkhole. The area of the sinkhole accumulation basin is quite small and is usually 0.01-0.1 km^2. Due to the difficulty of drainage, several hundred cubic meters of water can accumulate in the sinkholes. Regarding lakes in thermokarst sinkholes, it can be said that they form not due to significant water inflow but rather because of drainage difficulties. Water exchange in these lakes lasts for several years, unlike lakes in intramoraine depressions where water exchange occurs in a few days. Under certain conditions, subsurface runoff channels may thaw, unclog, and flow out of the lake. Our direct observations over the last 30 years and historical records have not revealed a single case of a hazardous breach of a thermokarst lake. They discharge water gradually at low flow rates, up to 1 m^3/sec, which is determined by the limited capacity of underground intraglacial drainage channels. The breaches of thermokarst sinkhole lakes do not have negative consequences for residents of mountain valleys.

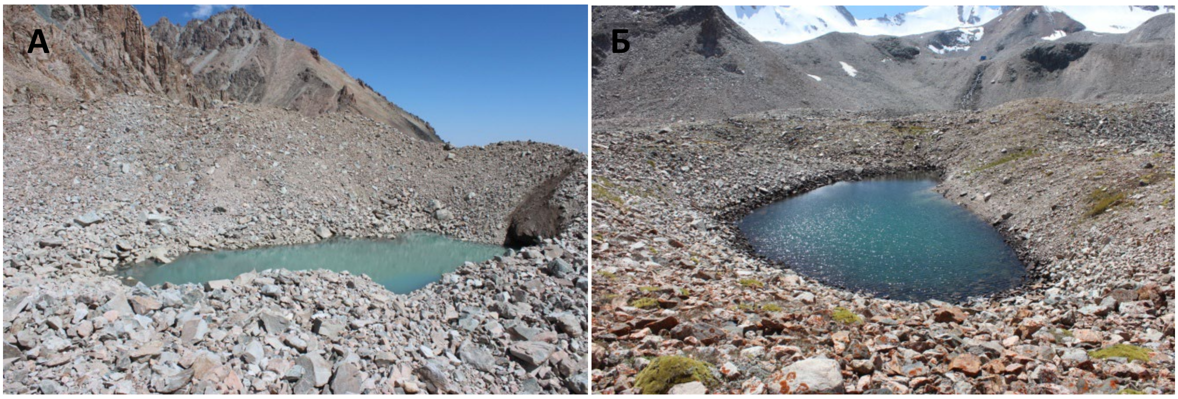

Fig.14.Thermokarst lakes of Adygene: A - Adygene 12T; B - Adygene 2T

Conclusion

From the above brief description of the three subtypes of moraine-glacial lakes, several important conclusions can be drawn:

1) outburst prone moraine-glacial lakes are formed in intramoraine depressions of the 3rd, 4th and 5th moraine-glacial complexes;

2) outburst prone moraine-glacial lakes do not form within the 1st, 2nd, and 6th types of moraine-glacial complexes.

3) lakes of the third subtype—thermokarst sinkholes—are formed on terminal moraine tongues and, less commonly, on terminal moraine ridges of moraine-glacial complexes of types 4 and 5. So far, there is no known case of lake breaches from thermokarst sinkholes with catastrophic consequences for residents of mountain valleys.

4) typification of moraine-glacial complexes makes it possible to determine the possibility of formation of glacial outburst lakes and to estimate the activity of mudflow processes in mountain valleys at present with a forecast for the future.

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