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RESEARCH PAPER

MODERN EVOLUTION AND HYDROLOGICAL REGIME OF THE BASHKARA GLACIER LAKES SYSTEM (CENTRAL CAUCASUS, RUSSIA) AFTER THE OUTBURST ON SEPTEMBER 1, 2017

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ABSTRACT. In high mountain areas, glacial lake outbursts are often the cause of floods and extreme events. Investigation of these events is especially important in the context of ongoing intensive deglaciation and climate change. This study is focused on the monitoring of the Bashkara Glacier Lakes after their outburst on September 1st, 2017, which are located in the most glaciated and populated part of the Central Caucasus of Russia, in the Mt. Elbrus region. Following the incident, the lakes system has transformed into flow-through. However, the lakes system has undergone significant changes and remains unstable and potentially hazardous. In this research, we used remote sensing data and field observations to assess the condition of the Bashkara Lakes. The water level, area and volume of the lakes are unstable. Between 2018 and 2024, the area of Bashkara Lake increased by 32% and volume by 41%, with the level increasing by 3.2 meters. At the same time, Lapa Lake was rapidly shrinking. The area of Lapa Lake in 2018-2024 decreased by 51%, the volume by 66%, and the level decreased by 4.2 meters. In addition to the continuing rise of the water level, the possibility of future rockfalls cannot be excluded, which can trigger a re-outburst. Ephemeral glacier lakes were also discovered, their merging with the main lake can cause a dramatic increase in the lake volume. On the other hand, other factors, such as the decrease in water temperature of Bashkara lake and its flowage, indicate the stability of the lakes system.

KEYWORDS: mountain hydrology, Central Caucasus, moraine-dammed lake, outburst, GLOF, Bashkara Lake

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INTRODUCTION

Continuing global warming affects the occurrence of glacier lakes outburst floods (GLOFs) in various mountain regions in the world (Lützow et al., 2023; Shrestha et al., 2023; Veh et al., 2022). A rise in the frequency of GLOFs in areas with extensive glaciers is anticipated by the end of the 21st century (Milner et al., 2017; Zheng et al., 2021). The study and prediction of flash floods is an important task in hydrology and has socio-economic implications, especially in mountainous areas where there is a limited number of measurement stations (Ali Washakh et al., 2024; Chen et al., 2019; Zhou et al., 2024), due to the ongoing intensive economic development of mountainous areas

The issue of studying the process of outburst flood formation, as well as identifying the triggering mechanisms and factors influencing lake outbursts, has received much attention in various studies (Awal et al., 2011; Costa and Schuster, 1987; Adam Emmer and Cochachin, 2013; Liu et al., 2013; Neupane et al., 2019; Westoby et al., 2014). There are external, internal and complex GLOF triggers, such as dam breach initiation caused by mass movement-induced impulse waves, lake overfilling due to pluvial, nival and glacial runoff (Taylor et al., 2023). Significant factors contributing to a glacial lake outburst flood include a rise in air temperature and heavy rainfalls, which necessitate careful consideration in light of the ongoing climate shifts (Allen et al., 2016; Din et al., 2014). While climate change is a major factor in the deglaciation, it also contributes to the weakening of glacier surfaces, which can lead to catastrophic failures of rock avalanches or other types of landslides (Shugar and Clague, 2011; Vilímek et al., 2014). GLOFs are frequently caused by the collapse of ice and rock, such as rockslides or moraine failures into lakes, resulting in the formation of seiches or displacement waves (Stephan Harrison et al., 2018).

Outburst floods caused by similar processes are observed in various regions of the world (Byers et al., 2019; Adam Emmer and Cochachin, 2013). The article (Shugar et al., 2020) examines the dynamics of glacial lakes and their distribution around the world based on satellite images from 1990 to 2018. It is shown that the number of lakes and their total area increased by 53% and 51%, respectively, during the study period. And the fastest growing lakes (in terms of area) are located in the Scandinavian countries, Iceland and Russia. The first global spatial and temporal assessment of outbursts floods from moraine and glacial lakes based on a regional review (165 moraine dams in the Alps, Pamirs, Tien Shan, Himalayas, USA and South America were selected) is presented in (Harrison et al., 2018). This article provides a historical view of outburst floods and their distribution under current and future global climate change. Currently, there are databases and catalogues of glacial lakes and their outbursts, created on the basis of space image interpretation (Emmer et al., 2016; Zhang et al., 2015).

A critical aspect in the investigation of outburst hazardous lakes is the exploration of the genesis process, evolution, and categorization of stages in their development. Currently, this subject receives limited attention, and scholarly works on the evolution of glacier lakes are few (Aleynikova and Anatskaya, 2019; S. Chernomorets et al., 2007; Dokukin and Khatkutov, 2016; Rasputina et al., 2022). Research shows that the evolution cycle consists of a number of stages, which can be called: 1) the stage of pre-catastrophic preparation, 2) the stage of a debrisflow disaster, 3) the stage of epicatastrophic adaptation, 4) the stage of inter-catastrophic evolution (Chernomorets, 2005). The article (Pryakhina et al., 2021) explores the evolution of the periglacial Lake Nurgan in Northwestern Mongolia, focusing on its stages of formation and development. These stages include the transgressive phase, characterized by the lake's growth, expansion, and increase in volume, the regressive phase, marked by the lake's outburst, and the post-regressive phase, during which the lake persists after the outburst.

Our study objects, the lakes Bashkara and Lapa, are located in the most glaciated and populated part of the Central Caucasus, in the Mt. Elbrus region. On September 1st, 2017, the Bashkara Lake outburst occurred with a total volume of 0.8 million cubic meters of water and 0.35-0.5 million cubic meters of debris (S. Chernomorets et al., 2018). After the outburst on September 1st, 2017, the lake system became permanent flow-through. However, this lake system has begun to evolve and change. The intensive retreat of the Bashkara Glacier took place during the last seven years: two ephemeral small lakes upper the lakes appeared, the size of Bashkara Lake was increasing, and of Lapa Lake was decreasing. Thus, the lakes system is unstable and still potentially hazardous.

Glacier lake may experience repeated outburst floods throughout its evolution (Carrivick and Tweed, 2016; Dussaillant et al., 2010; Adam Emmer, 2017; Kropáček et al., 2015; Petrasov, 1979; Poznanin, 1979) and even mechanisms of outburst formation can differ for the same lake at different events and stages of evolution. In August 1958 and 1959, as well as in October 1960, there were three Bashkara Lake outbursts through the grottoes in the ice wall, causing high-magnitude debris floods downstream the Adylsu River valley (Kovalev, 1964). In 2017, the lake outbursted trough dam erosion and successive glacial channel formation. Despite the formation of a well-developed run-off channel in 2017, it is possible that the lake can outburst again. For example, in summer of 2018 and spring of 2019, large rock falls were observed from Bashkara Peak (4162 m asl.) towards Bashkara Glacier, when rock avalanches had almost reached Bashkara Lake. In future, the possibility of repeated collapses is not excluded, considering the instability of the rocks on the mountain slopes around the lakes (Dokukin et al., 2020), that could trigger the repeated GLOF. Also the drainage channel that was formed follows the ice that is hidden in the moraine, i.e. erosion can be very intense due to thermokarst processes.

This study is focused on the monitoring of Bashkara Glacier lakes after their outburst on 1st September, 2017. The following steps were performed in the research: (1) Determination of the area of the lakes for different years using satellite images; (2) Analysis of changes in the water levels of Lake Bashkara and Lapa; (3) Assessment of the contributions of different water sources to the total outflow from Lapa Lake.

STUDY AREA

The Bashkara Glacier lakes system is located in the upper reaches of the Baksan River and the headwaters of the Adylsu River, its right tributary (Fig. 1). Bashkara Lake appeared in the early 1930s between the right lateral morine and the glacier and was surrounded by ice on three sides for a long time. Lapa Lake appeared at downstream the glacier's tongue in the 1990s. Nowadays, the distance between these two morine-dammed lakes is about 500 meters, the average altitude is from 2480 to 2580, relative excess between the lakes is about 100 meters. Over the past three decades, there has been a noticeable surface lowering at the snout of the Bashkara Glacier adjacent to the lakes. The area and volume of Lapa Lake significantly increased between 1999 and 2017, while Bashkara's size remained quasi-stable (Petrakov et al., 2012).

On the night of 31st August to 1st September 2017, an overflow occurred and a subsequent outburst of Bashkara Lake took place. This was triggered by an extremely heavy rainfall accompanied by strong wetting of the moraine dam. The total precipitation recorded at the Djankuat station near the lake during the night was approximately 100 millimeters (mm) per hour. As a result, significant damage was observed both in the Adylsu River valley, with the total length of 11.5 km, and in the Baksan River valley at a distance of more than 50 km downstream the mouth of the Adylsu River. (S. Chernomorets et al., 2018; Kornilova et al., 2021).

The pre-outburst water level of Bashkara Lake was approximately 2672 meters. According to data from the water level logger, the level in the lake rose by 55 centimeters (cm) in 5 hours during the rainstorm. This led to the erosion of the dam crest during outflow, and the water level in Bashkara Lake dropped by 17 meters relative to its pre-outbreak level. The water volume of Bashkara Lake after the outburst decreased by more than ¾, from more than 1 million m3 to approximately 290 thousand m^3. The GLOF wave first moved from Bashkara Lake across the surface of the glacier's tongue, partially drained Lapa Lake, and then flowed downstream the Adylsu River valley.

At present, lakes Bashkara and Lapa represent a complex system. The Bashkara Glacier supplies water to both the upper and lower lakes. Water from Bashkara Lake flows through a glacier tunnel and feeds Lapa Lake. Lapa Lake is drained by well-developed surface run-off channel to the Adylsu River valley.

MATERIALS AND METHODS

Remote sensing data

We used Sentinel-2, Pleiades and SPOT 6 satellite images to estimate changes in lake area. Typically, the summer months of July through September are considered the ideal time for glacial lake mapping (Zhang et al., 2015). During this time, the amount of snow and ice coverage is minimal, and the area of glacial lakes reaches its maximum. Therefore, we here acquired the best possible images during this period. The collected images were screened for cloud cover and selected for cloud cover <10 % to ensure data reliability. Images were selected for each year from 2017 to 2020 (table 1). We manually mapped the shoreline on all the images using ArcMap 10.4.1.

We examined the area change in Bashkara Glacier during 2017–2024 using Sentinel-2 satellite images. We selected images at the end of the ablation season, when seasonal glacier retreat is maximum (Popovnin et al., 2024).

Hydrological measurements in a lake system

Water level and temperature

Since September 1st, 2017, we continued annual systematic observations of the level of Bashkara Lake using automatic water level recorders, which were initiated in 2007, to monitor the risk of a potential re-outburst (Fig. 2c). In 2018, 2019, 2023 and 2024 we installed water level and temperature loggers Keller to record every 15 minutes data, and also monitored the lake levels relative to a geodetic reference. These measurements are critically important for monitoring the situation and ensuring the safety of the surrounding area. We compared our measurements with the data observed before the outburst from 2007 till 2017 (Petrakov et al., 2012, Chernomorets et al., 2018). The accuracy of the measurements is 0,1% FS.

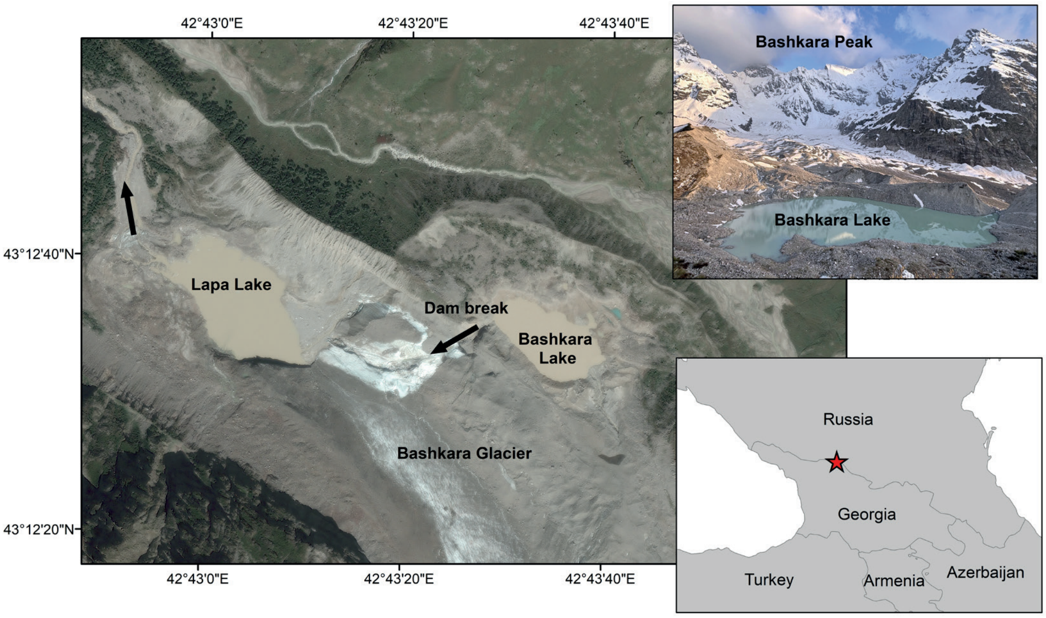

Fig. 1. Study area

Table 1. Multi-source remote sensing datasets

Date	Satellite image	Resolution, m	Objectives
01.08.2017	Pleiades	0.5	Lake area changes
03.09.2017	SPOT 6	1.5	
29.07.2018	Sentinel-2	10	
27.07.2019	Sentinel-2	10	
16.07.2020	Sentinel-2	10	
18.07.2021	Sentinel-2	10	
28.07.2022	Sentinel-2	10	
26.07.2023	Sentinel-2	10	
30.07.2024	Sentinel-2	10	
13.08.2017	Sentinel-2	10	Glacier retreat assessment
30.09.2017	Sentinel-2	10	
28.09.2024	Sentinel-2	10	

Depth measurements

In September 2020, we conducted bathymetric surveying with a boat-mounted Lowrance 525 CF two-frequency echo sounder which produced geo referenced echograms. Sounding points were located along cross-sections at 15-30 m intervals. Surfer 15.3 and ArcMap 10.4.1 software were used to calculate lake volumes and average depths.

Water discharges

From 2018 to 2020, we measured water discharges at various gauging stations in the lakes system to study the hydrological regime of the newly formed flow channels. We installed several discharge gauging stations on streams: Bashkara, Dam Break, Dam Break after the glacier, Lapa (Fig. 2a). Over a period of three years, we collected 20 series of discharge measurements (including four discharges per series). Within each series, we were measuring discharges at each gauge on the same day for two to three hours. Simultaneously, we also measured water levels of both lakes on water level stations (Fig.2a).

The water discharges were measured using the salt dilution method (Fig. 2b). The salt dilution method is an easy-to-use technique for measuring discharge in small turbulent streams that are typically found in mountain areas. To control and compare the results, the water discharges were measured twice at each gauge. The relative error was then calculated. If it was less than 15%, the discharge was considered well-measured.

RESULTS

Glacier retreat assessment

Due to the high thickness of debris-cover on the Bashkara Glacier, it is difficult to estimate the accurate area reduction. However, the retreat of the glacier tongue is clearly visible on the images. According to Sentinel-2 image interpretation data, the area is rapidly decreasing (Fig. 3). The total retreat of the glacier tongue from 2017 to 2024 was about 210 meters.

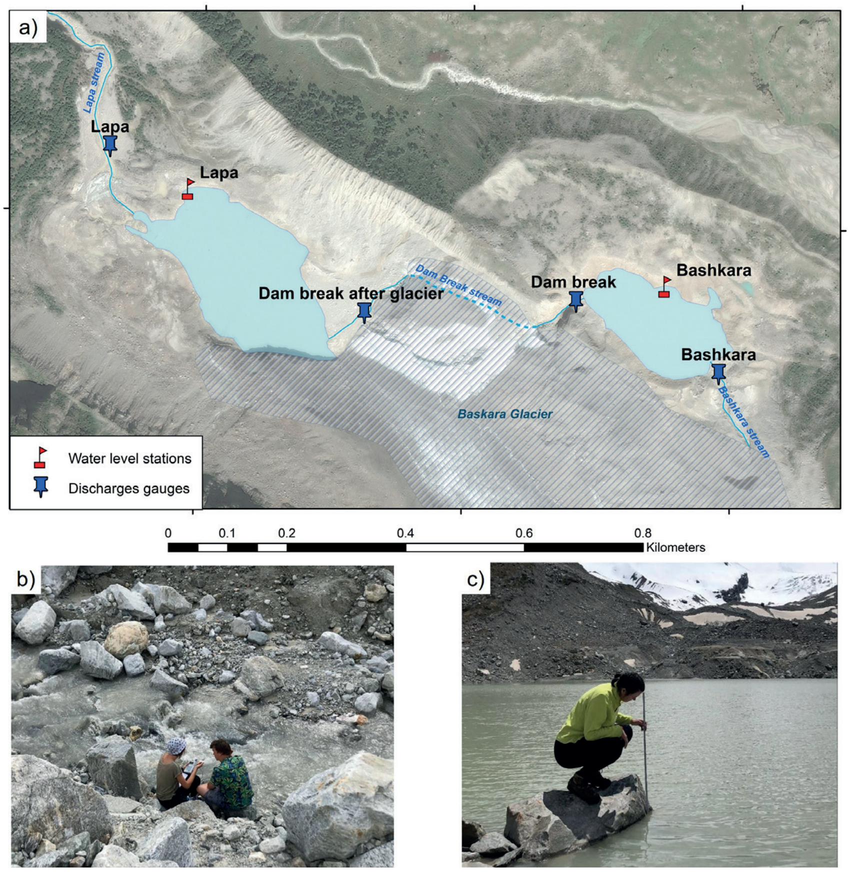

Fig. 2. Location of gauging stations (a), measurement of water discharge by salt dilution method (b) and water level measurement during the logger installation (c)

Fig. 3. State of the Bashkara Glacier in 2017 before and after the outburst and in 2024

Changes in the area, level and volume of lakes

Despite the fact that the lake is flow-through, its level, area, and volume are unstable both seasonally and over several years. The area and volume of Bashkara Lake vary between 26,000–35,000 m^2 and 239,000–339,000 m^3, respectively. We observed that during the period 2018-2020, the area of Bashkara Lake was nearly constant, but it began to expand after 2021 (Fig. 5a). In 2018–2024 the area increased by 32% and the volume increased by 41%. Since the outburst on 1 September 2017, the water level has risen by 3.2 meters, mainly between 2021 and 2024. The maximum measured depth (17,5 m in 2020) was in the center of Bashkara Lake (Fig. 4). Since 2018, the lake bed relief slightly reshaped, as confirmed by the changed volume curve (Fig. 5c). This is probably due to the continued accumulation of sediment on the lake bed. It is also worth noting that the area of ephemeral lakes, formed by uneven deposition of surface moraine on the glacier and in the ice flow stress zones, is increasing.

At the same time, Lapa Lake experienced a rapid decrease (Fig. 5b). Between 2018 and 2024, the level of the lake decreased, which was driven by the glacier tongue retreating, debris sedimintation and siltation (Fig. 4b). sediments from the debris-covered tongue of the Bashkara Glacier form a delta in the southern part of the lake. In 2018–2024 the area decreased by 51%, the volume decreased by 66%, and the water level decreased by 4.2 meters. The maximum depth measured in 2020 was 8.5 meters in the center of the lake. The relief of the lake bed is heterogeneous, with two local depressions, separated in the north-eastern part by a former underwater ridge that has now dried up. It is likely that the lake will split into two in the future. This was already the case in the past, in the late 1990s and 2000s. Initially, two distinct lakes, Lapa and Mizinchik, were formed. Subsequently, these lakes underwent a process of merging.

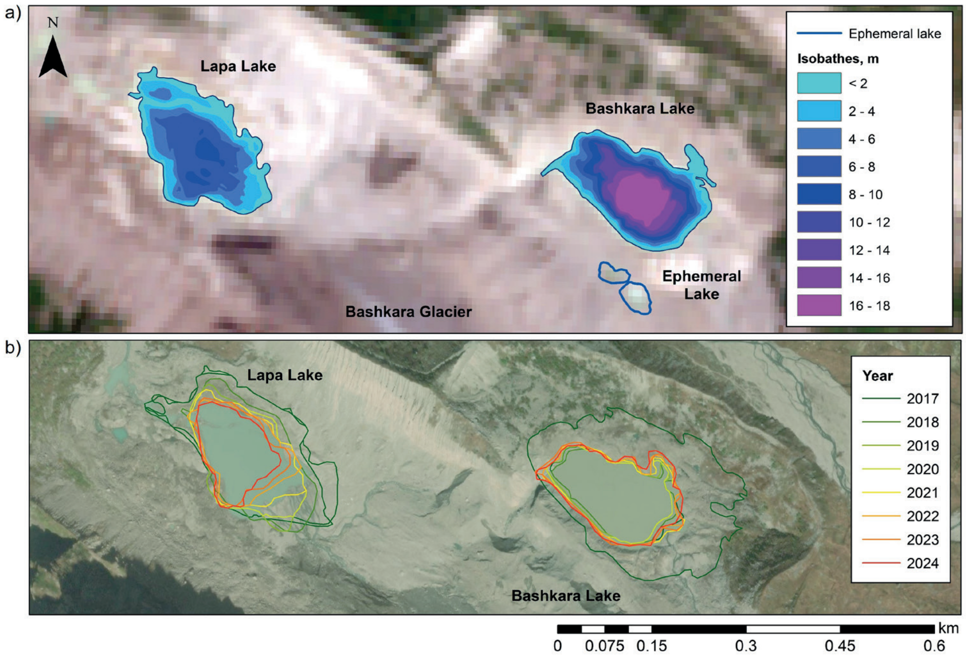

Fig. 4. Bathymetric map of Bashkara and Lapa lakes in 2020 (a); Changing the shape of Bashkara and Lapa lakes (b)

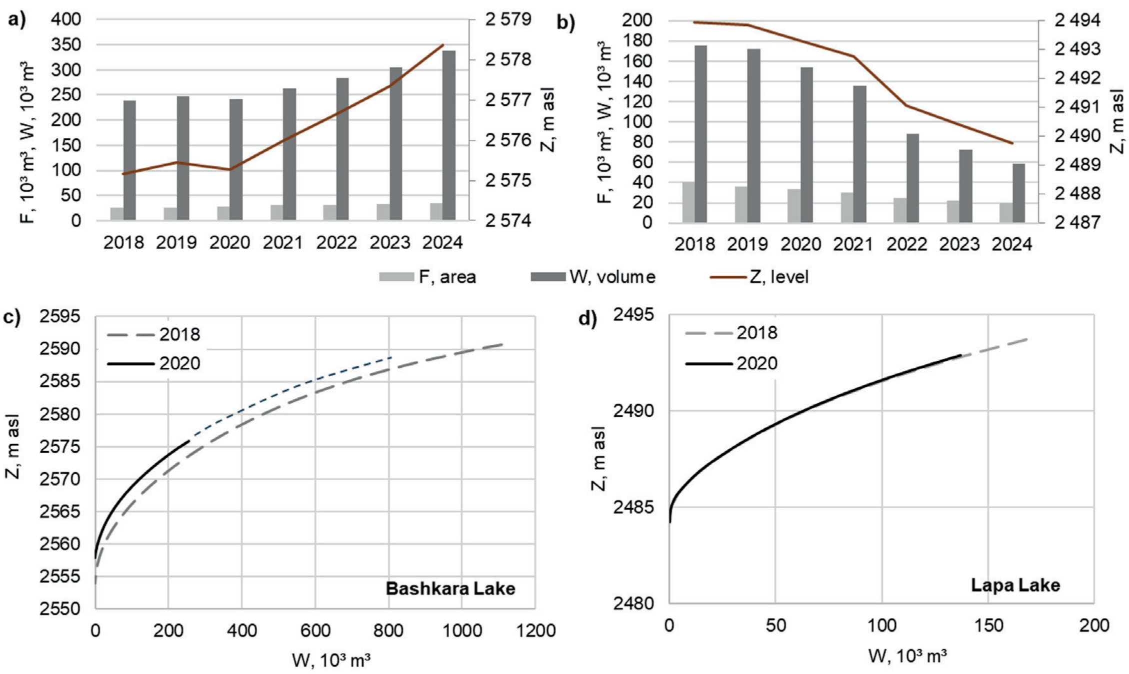

Fig. 5. Area, level and volume change in 2018–2024 of Bashkara Lake (a) and Lapa Lake (b); volume curves of Bashkara Lake (c) and Lapa Lake (d)

Water level fluctuation

Bashkara Lake water level is one of the most important indicators of its re-outburst hazard. After September 1st, 2017 Bashkara Lake is drained by a well-developed run-off channel, so water level fluctuations during the warm season are not high. During summer the lake level varies within a range of 20-50 cm, and remains quasi-stable until late summer. Lake levels sometimes rise sharply in the short term due to intense melting of ice and snow or heavy rainfall. The lake level would decrease to a minimum at the end of the ablation period in late September. October (Fig. 6). However, before the outburst in 2007-2017 the intra-annual water level fluctuations were higher, around 150-300 cm, with the highest level usually observed in June. During the summer of 2008 the level rise was about 400 cm. In 2008, the overflow through the ice-cored moraine dam into the englacial drainage system began due to the lake level increase. However, the surface runoff stopped, the lake didn't burst and the water level stabilised in the following year.

Lake temperature fluctuation

An indirect indication of the state of the lake is its water temperature and its long-term dynamics. In the past, Lake Bashkara was non-flowing and therefore heated up near the shore and on the surface to a depth of 1.5-2 m. The lake is currently flow-through with a short water retention time. At the same time, the main source of water inflow is cold glacial meltwater, resulting in a decrease in the average water temperature of the lake compared to the pre-outburst state. The average water temperature of the lake from June till September was 7.8°C before the lake outburst in 2013-2016; in 2017, as a result of intensive snow and ice melt, the temperature was 3.9°C; after the outburst, the temperature was 1.6°C (Fig. 7b).

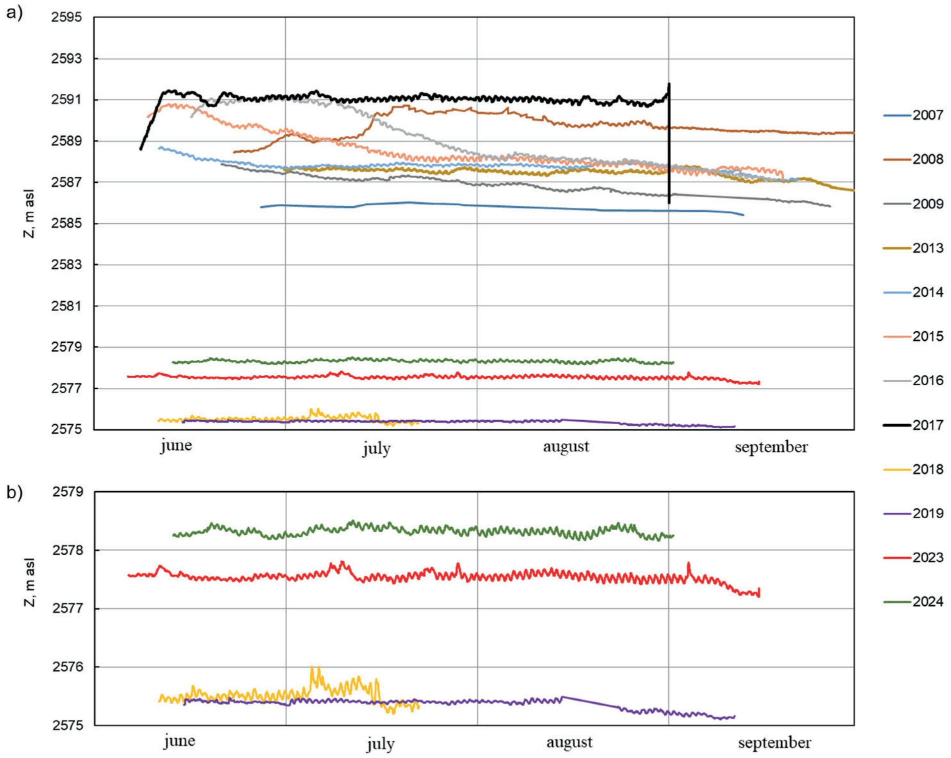

Fig. 6. Lake Bashkara water level fluctuations during warm periods in 2007–2024 (a) (Chernomorets et al., 2018; Petrakov et al., 2012), in 2018–2024 (b)

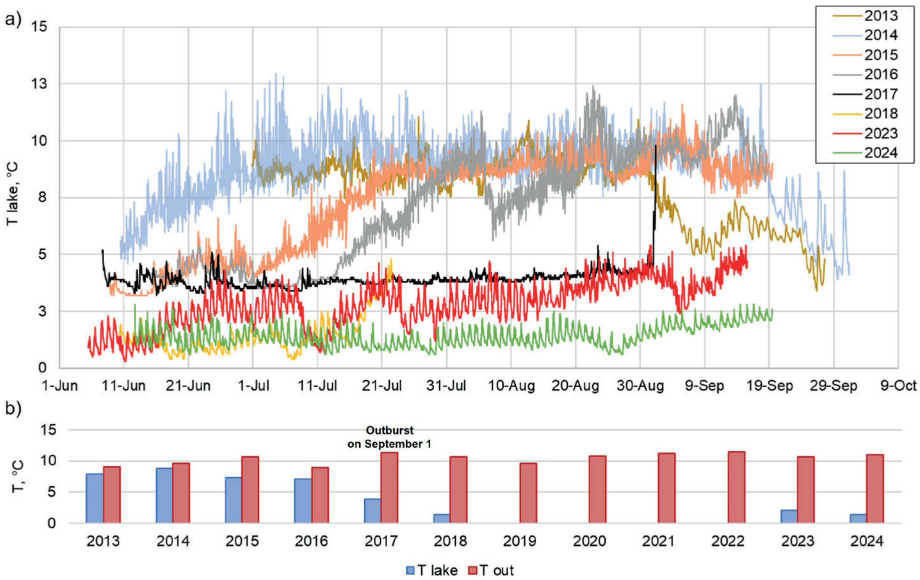

Fig. 7. Lake Bashkara temperature fluctuations during warm periods in 2013–2024 (a), average air (T out) and lake (T lake) temperature from June to September in 2013–2024 (b)

The water temperature fluctuations are in an inverse relationship with the water level: when the water level decreased, the water temperature increased and vice versa (Fig. 7a). This is due to the fact that during periods of low water, the intensity of cold meltwater runoff from the mother glacier decreases and the water mass of the lake warms faster.

Hydrological regime of the Bashkara Glacier Lakes system

For the period 2018-2020, Q(H) curves were plotted for streams flowing from two lakes, Bashkara and Lapa (Fig. 8a,b). Both dependencies were not stable from year to year, indicating the instability of the lake system. Average measured discharges were from 0.1 till 2.4 m^3/s. This is particularly evident for Lapa Lake, because it has changed significantly in size and shape in 7 years due to intensive glacier retreat. After 2021, the discharge of the Dam Break stream visually increased significantly, the water level rose and flooded the shores (or the floodplain), making it impossible for measurements. According to the measurement results, the Dam Break stream is additionally fed by meltwater from the inside the glacier tunnel, as the discharges of the Dam Break stream downstream the glacier were always higher than upstream.

Lake Lapa also receives a large amount of meltwater directly from the Bashkara Glacier tongue. However, as it is impossible to measure the total meltwater inflow, it was assesed by subtracting the contribution of the Dam Break stream from the total outflow from Lapa Lake. The results show that the meltwater from Bashkara Glacier is the largest contributor to the Lapa stream discharge, averaging 65% of the total outflow. The contribution of the Dam Break stream, i.e. water from the upper lake, is small, averaging 24%, and the glacier cave meltwater is 11% (Fig. 8d,e). However, it is likely that this balance has changed in recent years as a result of opposite trends in the level, area and volume of the two lakes.

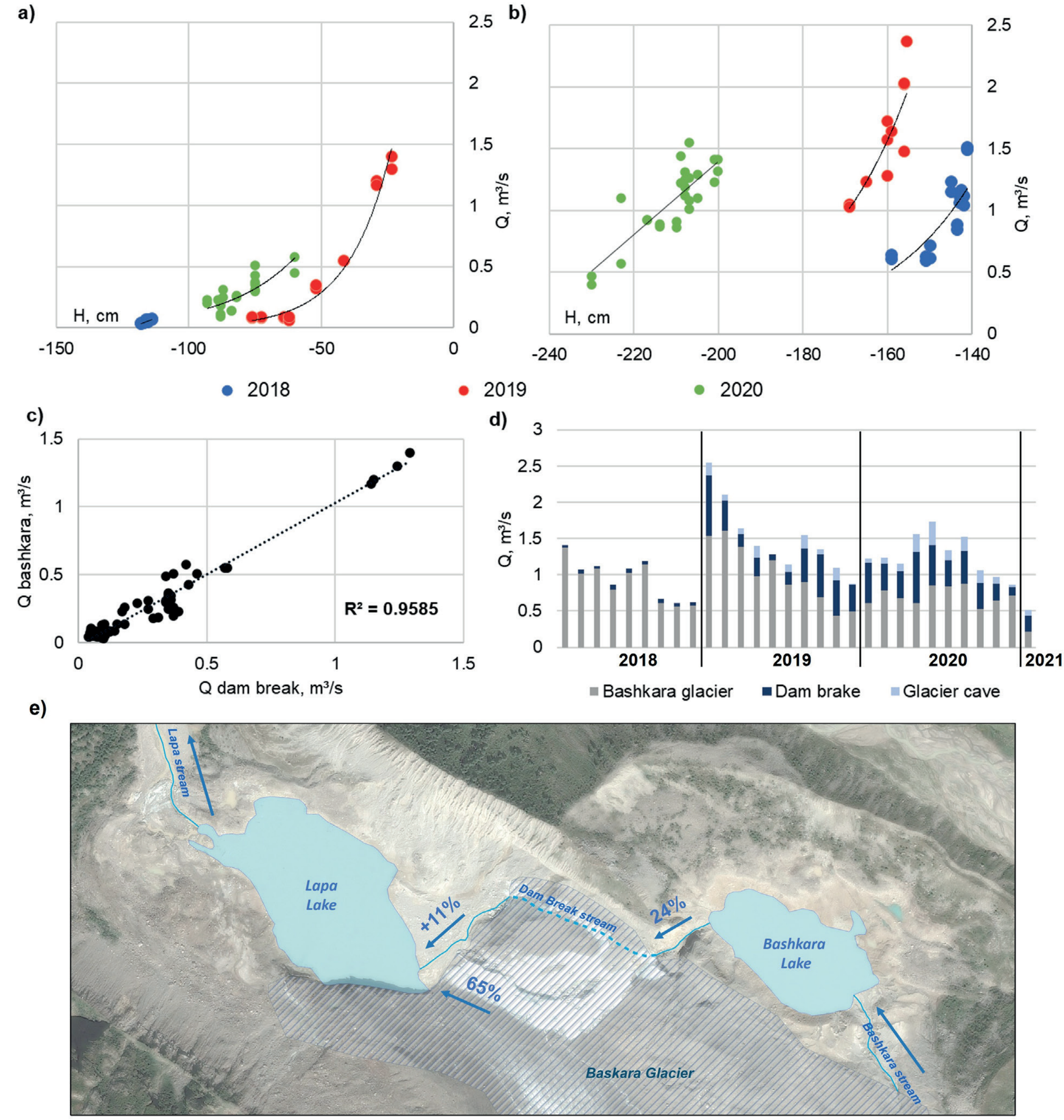

Fig. 8. Q=f(H) curves of Dam Break stream (a) and Lapa stream (b); correlation between discharges of the Bashkara and Dam Break streams (c); contribution of different sources to the total outflow from Lapa Lake (d); spatial distribution of different sources to the total outflow from Lapa Lake (lake outlines of 2018) (e)

DISCUSSIONS

The Bashkara lakes system has gone through several stages of formation and development since its appearance in the 20th century (Fig. 9). The stage of pre-catastrophic preparation, characterised by the growth of the lakes, their area and volume, lasted ~1960 till 2017. Then came the stage of the debrisflow disaster, when Bashkara Lake bursted on September 1st, 2017. From 2018 to 2020, the lake system was quasi-stable; this was the stage of epicatastrophic adaptation. After 2021, however, the volume and area of Bashkara Lake began to increase, marking the transition to the stage of inter-catastrophic evolution. The whole glacial complex is a rather complicated hydraulic system and requires further monitoring of its water balance and dynamics.

A number of factors indicate that the risk of another outburst from Lake Bashkara is on the rise. As before the outburst, there has been a stable trend of intra-annual increases of the water level of Bashkara Lake. In 2018-2019, we did not observe an intra-annual increase of the water level of Bashkara Lake, but in 2023 it was 160 cm higher than 4 years earlier. This trend continued in 2024: the water level was about 60 cm higher than the year before. Extrapolating the *Q=f(H)* curve to the current water level of Bashkara Lake, it can be concluded that the summer discharge of the Dam Break stream could reach 5-6 m^3/s in 2024. The area of ephemeral lakes within the Bashkara Glacier increases. The reduction of the width of the ice-debris dam and its destruction between them and Bashkara Lake could also lead to an outburst. In addition, other factors of moraine complex reformation due to glacier retreat like ice collapses, thermokarst subsidence at the lake bottom, extension and retreat of the delta of the stream flowing into the lake, slope processes on the shores can lead to an unstable condition of the lake. Our observations correlate with glaciologic studies of the potential glacial lake development in the Central Caucasus (Lavrentiev et al., 2020), which predict that Bashkara Lake is expected to continue growing, and the risk of the possible repeated lake outburst is high.

On the other hand, a number of factors indicate a certain stability of the Bashkara lakes system in recent years. According to the results of the water balance study for 2018-2024, the inflow of the Bashkara stream was always close to the outflow of the Dam Break stream, moreover, the flow of the Bashkara stream, the water lake level and the flow of the Dam Break stream correlate with ablation of the Bashkara Glacier (Fig. 8c). This proves that the lake does not have any additional 'hidden' inflow channels and that all the meltwater coming from the catchment leaves the lake via the Dam Break outflow. Consequently, the lake is a self-regulating system as a result of the constant outflow. It also should be noted that the average water temperature of the lake decreases annually in summer (a possible sign of the increased inflow), which reduces the rate of debris-covered dead ice melting.

CONCLUSION

In the seven years since the outburst on September 1st, 2017, there have been significant directional changes in the water level, area and volume of Bashkara Lake, with relatively small seasonal variation. Between 2018 and 2024, the area of Bashkara Lake increasesв by 32% and the volume by 41%. At the same time, Lapa Lake has shrunk in size due to silting. Between 2018 and 2024, the area of the lake decreased by 51% and the volume by 66%.

At present, Bashkara Lake is drained by a well-developed surface run-off channel and the water level fluctuations during the summer season are insignificant. The lake level varies within 20-50 cm and remains practically stable until the end of the warm season. At the same time, there has been a directional increase in the water level of Bashkara Lake over the last 5 years. From 2020 to 2024, the lake summer water levels have risen by 3.2 meters.

For the period 2018-2020, *Q(H)* curves were constructed for rivers flowing from the two lakes, Bashkara and Lapa. Both dependencies were not stable from year to year, which also indicates the instability of the lakes system. The results of the water balance studies show that the outflow from Lapa Lake approximately contains of Bashkara Lake runoff (35%) and Bashkara Glacier runoff (65%) (excluding the Bashkara Lake catchment area). Except the inflow from Bashkara Lake, water flows into Lapa Lake in two main ways. About 11% of the total amount of meltwater flows through a sub-glacial channel, which has an outlet at a glacial cave. The rest, about 24%, is dispersed as sub- and inter-glacial meltwater inflow. However, it is likely that this balance has shifted in recent years as a result of opposite trends in the level, area and volume of the two lakes. After 2021, the warm season flow from Bashkara Lake through the surface channel (the 'Dam Break' channel) has visually increased significantly. Extrapolation of the *Q=f(H)* curve to the Bashkara Lake water level in 2024 shows that the discharge through the Dam Break stream could reach 5-6 m^3/s.

It can be concluded that the entire system of the Bashkara moraine-glacial complex, including the glacier, the lakes and the runoff system, has moved from the stage of epicatastrophic adaptation (2017-2020) to the stage of

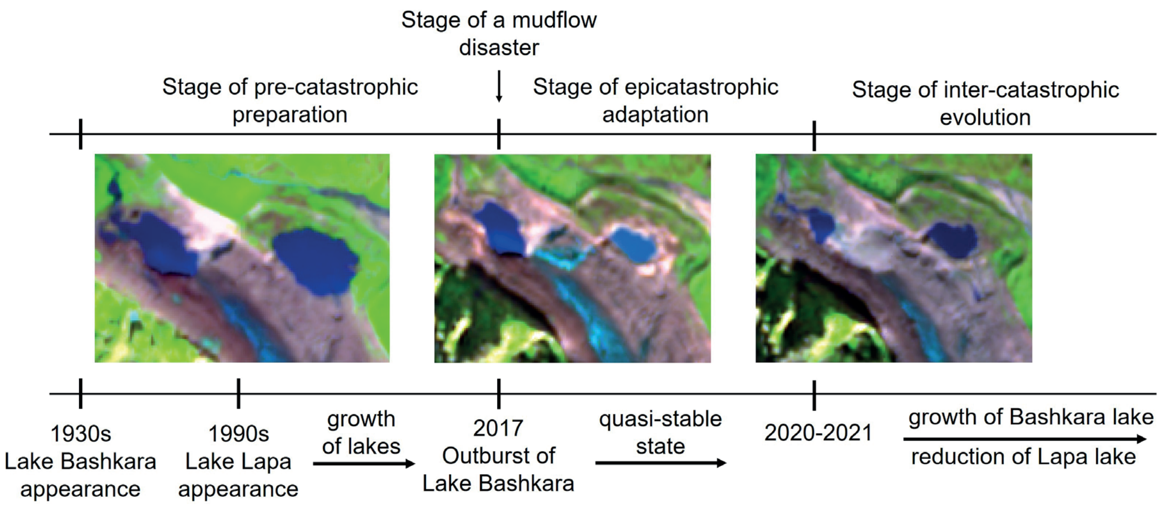

Fig. 9. Stages of formation and development of the Bashkara Lakes system

inter-catastrophic evolution (according to the classification of Chernomorets, 2005).

The results demonstrate the necessity for further monitoring of the glacial complex, i.e. repeated bathymetric surveys, observations of lake sedimentation and siltation, lake temperature surveys and water level measurements. The identified features will allow to identify similar patterns for other glacier lakes in the region. It is also necessary to take measures to reduce the level of Bashkara Lake to prevent it from re-outburst.

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