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Debris flow hazard of glacial lakes in the Central Caucasus

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ABSTRACT: Glacier retreat is accompanied by formation of lakes within glacier moraines. The lakes may produce outburst floods which can transform into destructive debris flows. In the Central Caucasus this hazard has not been sufficiently studied, and the location and size of glacial lakes is not shown on the topographical maps. We have combined field and remote sensing research to study glacial lakes and debris flow initiation zones in periglacial areas. Two case studies are presented. Bashkara lakes in the upper Adyl-Su River valley have been subject to detailed monitoring since 1999. In 2005 their total area reached 93,000 m^2, and the total volume exceeded 900,000 m^3. Buildings, bridges and camping sites are in areas endangered by potential debris flows. A second group of 13 glacier lakes was identified in 2005 on the northeastern slopes of Mt. Elbrus. In July 2006 the area of the largest lake reached 89,000 m^2, and its volume was 550,000 m^3. On August 11, 2006 the lake produced an outburst flood releasing about 400,000 m^3 of water which later transformed into a debris flow that entrained up to 350,000 m^3 of solid material. A downstream mineral water resort was damaged. We have identified 71 glacial lakes in the Central Caucasus. These include post-disaster lakes, e.g. in the Genaldon River valley where 13 new lakes formed after a glacier disaster in 2002, which at one point reached 437,000 m^2 in area and 5,000,000 m^3 in volume. In the future we hope to develop detailed recommendations for risk management of glacier and debris flow hazards in the Central Caucasus.

1 INTRODUCTION

Glacial debris flow activity is driven by climate and weather conditions as well as by glacier dynamics and geological features. In recent decades alpine glaciers have been shrinking worldwide. After the termini retreat the vacant areas are taken over by moraine debris and proglacial lakes. Lake formation is currently observed in the majority of glaciated mountain regions of the world (the Himalayas, Andes, Alps etc.). Often dammed by ice-cored moraines, glacial lakes are one of the main sources of devastating outburst debris floods. These outburst floods often transform into even more destructive debris flows when the flow path is steep, flow velocity is high and erodible material is available (e.g., Clague et al. 1985; Clague & Evans 1992; Huggel et al. 2004; Kääb et al. 2005; Chiarle et al. 2007), threatening tourists and the population of downstream mountain valleys. So far, potentially dangerous sites such as moraine- and ice-dammed lakes are not systematically surveyed. It is extremely important to improve our knowledge of glacial-lake formation features, estimate lake volumes and areas, and assess the hazard of outburst floods and debris flows.

In comparison with other glacier hazards, glacial lake outburst floods (GLOFs) are widespread and highly recurrent. According to a representative dataset (Richard & Gay 2003), since mid-16th century there were 671 glacial disasters in the Alps, including 338 GLOFs. Up to 60% of the victims of these events died due to GLOFs and consequent debris flows. Although these statistics are not representative of other regions, we suppose that the picture is typical for many high mountains worldwide.

For this simple reason glacial lakes are being studied in different mountain regions. One of the main goals is detection and inventory of the potentially hazardous lakes. Glacial lake formation and its consequences were studied in the Himalayas (Richardson & Reynolds 2000; Vuichard & Zimmermann 1987; Mool et al. 2001), Cordillera (Clague & Evans 2000), Alps (Huggel et al. 2002), and Andes (Lliboutry et al. 1977). A sudden outburst may lead to vast damage and victims. For example, part of Huaraz city in Cordillera Blanca, Peru, was annihilated due to Palcacocha lake outburst in 1941; more than 5,000 people were killed. Lake Dig Tsho burst in 1985 in Nepal leading to destruction of a hydropower plant, with damage of about (U.S.) $500 million (Richardson & Reynolds 2000). The damage caused by the Machu Picchu hydropower plant destruction in Peru in 1998 was (U.S.) $160 million (Reynolds 2003).

In spite of such damages the debris flow danger of glacial lakes has not yet been sufficiently researched. Up to now, even in the Alps conclusions are drawn mainly on the basis of small amounts of direct field data. Lake volume is estimated mainly using empirical ratios with area (Huggel et al. 2004), but the error may be up to 80%. The outburst trigger mechanism is poorly understood as well as the relations between the lake volume and the debris flow discharge. More data are needed to improve modelling accuracy. In the Caucasus, a highly glaciated mountain range up to 5642 m a.s.l. between the Black Sea and the Caspian Sea (Fig. 1), debris flows initiated by glacial lake outbursts are under-studied. Nevertheless several such events occurred in the region during the 20th century. In 1909 a popular mineral water resort on the NE slopes of Mt. Elbrus was destroyed by a debris flow originated by GLOF from a lake near the Birdzhaly-Chiran glacier terminus (Gerassimow 1909). Glacial lake Bashkara burst through an ice-cored moraine dam twice in the late 1950s and produced devastating debris flows of ca. 2 million m^3 (Seinova & Zolotarev 2001).

In recent decades many new lakes have formed in the Caucasus due to rapid glacier recession induced by climate change (Stokes et al. 2006; Shahgedanova et al. 2007). Increase of July and August temperatures almost by 1°C in the last forty years (Petrakov 2006) raises the risk of lake outbursts due to accelerating melting of ice in the lake dams. Ice blocks in the moraine dams serve as a waterproof cementing layer and prevent rapid outbursts. When that ice melts, the probability of an outburst rises (Petrakov et al. 2004). We estimate that currently there are up to 70 significant glacial lakes in the Central Caucasus. Location and size of the new lakes is not shown on the topographical maps, which were compiled for this region some fifty years ago. Overall, the current state of the lakes and their potential hazard are not fully clear (Chernomorets 2005). In the case of lake outbursts consequences may be catastrophic.

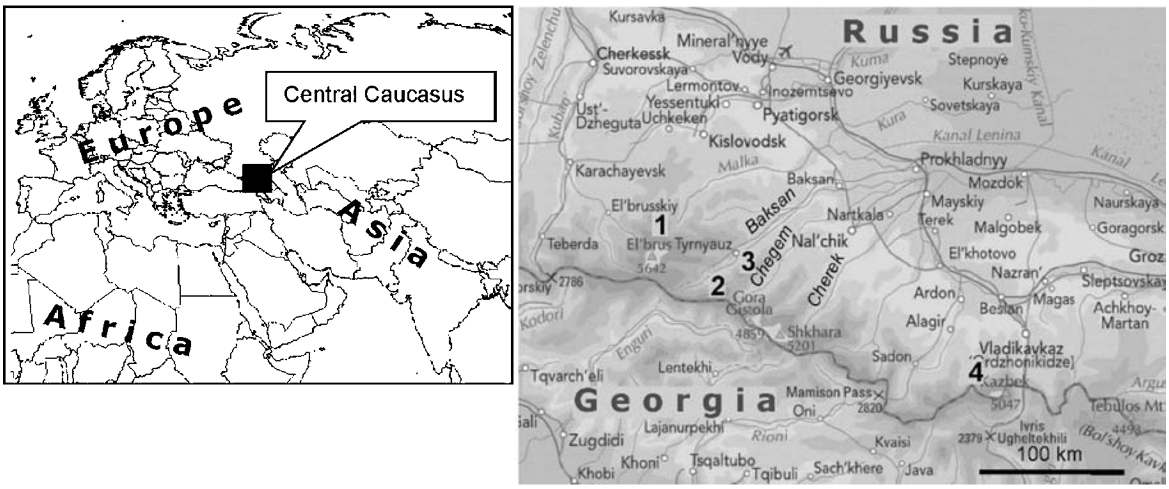

Figure 1. Location of the study region. 1 – Bashkara lakes; 2 – NE slope of Mt. Elbrus; 3 – Gerkhozhan-Su River valley; 4 – Genaldon River valley.

Specific aims of our study are as follows: i) to describe glacial lake formation in the Central Caucasus; ii) to determine the main drivers of glacial lake area, volume and level dynamics; and iii) to assess debris-flow hazards due to lake changes, formation and bursts.

2 MATERIALS AND METHODS

We have selected an accessible key site to study lake formation and change process: a group of glacial lakes near the Bashkara glacier in the upper Adyl-Su River valley, to the southeast of Mt. Elbrus. We have monitored these lakes for seven years. Our work included detailed field research as well as aerial and satellite image analysis. Level gauge measurements began in summer 1999 and have been repeated annually in the warm (June-September) period. In the beginning lake levels were measured several times per summer, but in the last few years they were measured daily or twice a day in July and August. These measurements were accompanied by measurements of air temperature, precipitation and glacier ablation.

Geodetic surveying of the lakes started in 1999. We have used Zeiss Theo 010 B and Theo 020 optical theodolites, as well as a Zeiss Photheo 19/1318 photo-theodolite with a 190 mm lens and 13 cm $\times$ 18 cm glass plates, and geometrically calibrated consumer-grade digital cameras. Calibration was carried out by R.N. Gelman using his own method (Gelman 2004). We have compiled topographic maps of this area for 1999 and 2005, as well as cross sections and longitudinal profiles for the downstream area. Bathymetric surveying with a boat-mounted GPSmap188 sounder has been repeated annually since 2001. The device contains a GPS receiver and a two-ray echo sounder working in the 50-200 kHz frequency band. It is capable of measuring water depths from 0.5-100 m with an estimated error of less than 0.3 m. Sounding points were located along cross sections spaced at 15 to 30 m. The horizontal location accuracy was within 5 m. For calculations of lake volumes, average depths, and lake bed deformations we employed Surfer 8.0 and ArcView 3.2 software.

In addition we compared old topographic maps (surveyed in 1957-1962) and recent remotely sensed images (Landsat ETM+, Terra ASTER, Quick Bird, images from International Space Station, and aerial imagery, all taken in 1999-2005) to estimate changes in lake numbers and areas in river basins of the Central Caucasus. In this article we present detailed results for the largest glacial lake site in the Central Caucasus, situated in the upper Malka River basin on the northeastern slopes of Mt. Elbrus. During fieldwork we surveyed coastlines and measured water depths of the main lakes at this site, using methods described above. We have investigated moraine dams of these lakes, river channels and valleys, as well as downstream settlements and infrastructure to identify the most dangerous lakes.

3 CASE STUDIES

3.1 *Bashkara glacial lakes*

The Bashkara group of glacial lakes with a total area of 93,000 m^2, and a total volume over 900,000 m^3 is located in the upper part of Adyl-Su basin at the margin of Bashkara glacier (Fig. 2). This valley-type glacier is roughly 4 km in length and has an area of about 3 km^2. The main branch of the glacier flows from Mt. Ullukara (4302 m a.s.l.) to the north and turns to the northwest at the snout. A secondary branch issues from a mountain pass between Mt. Bashkara (4164 m a.s.l.) and Mt. Dzhantugan (4012 m a.s.l.). This branch descends towards the northwest and flows into the main branch in the upper part of the snout. During the Little Ice Age (LIA) the glacier snout was divided into two parts as a result of the main Ullukara branch pushing the Bashkara branch out to the right side of the valley. As a result, a moraine ridge loop was created. In late 1940s - early 1950s Lake Bashkara started to form inside the loop due to the stagnant ice melt. The lake was not shown on a schematic map of the Bashkara glacier in 1933 (Oreshnikova 1936), and did not yet exist in 1946 (E.A. Zolotarev pers. comm.). However, it was shown on a 1957 schematic map (Dubinsky & Snegur 1961). At that time the lake area was two times less than today. A second smaller lake downstream of the glacier snout is also mentioned in the

Figure 2. Bashkara lake group. 1 – Bashkara Glacier, 2 – Lake Bashkara, 3 – Lake Lapa, 4 – Lake Mizinchik. Photo by V.V. Krylenko.

literature. In August 1958 and 1959 Lake Bashkara burst through its ice dam. After these GLOFs the level of the lake was lowered by two meters. The smaller downstream lake was also involved in the flood. As a result catastrophic debris flows totalling 2 million m^3 were formed from the moraine deposits and travelled 12 km downstream. The initial water impulse was only 60,000 m^3 (Seinova & Zolotarev 2001).

In the end of the 1980s new small lakes formed south of the drained downstream lake by the edge of the retreating Bashkara glacier (Seinova & Zolotarev 2001). In 1991-2001 these lakes grew in area and volume (Chernomorets et al. 2003) but, in our opinion, their outburst was unlikely due to small volume of the lakes and relatively good surface drainage. The larger eastern lake was named Lake Lapa and the smaller western lake was named Lake Mizinchik (Fig. 2). Lake Bashkara has subglacial/englacial drainage which goes towards these downstream lakes. Lakes Lapa and Mizinchik are dammed by a low ice-cored moraine. Should the drainage channel of Lake Bashkara become cluttered, a catastrophic GLOF involving all three lakes may occur. It is likely to erode downstream moraine and debris flow deposits and transform into a debris flow. The situation becomes more dangerous each year. Buildings, bridges and camping sites may be damaged.

3.1.1 *Lake level dynamics*

Water level of a glacial lake is one of the most important indicators of short-term outburst hazard. Lake Lapa is drained by a well-developed runoff channel, so the water level variations are not large. During summer the range of variations is about 10-15 cm, while the seasonal range does not exceed 30 cm. The interannual lake level is also stable.

For Lake Bashkara the situation is different. We conducted detailed field investigations to identify the influence of ablation and rainfall on lake level fluctuations. The seasonal range of levels is up to 150-200 cm (Fig. 3), with the highest level usually observed in the beginning of the warm period. In late June-early July the level goes slightly down and remains quasi-stable until late summer. In the last week of August to first week of September lake level sinks rapidly and we observe its minima at the end of the ablation period. There is no surface drainage channel from Lake Bashkara. Its water filters through englacial channels and cavities in the stagnant part of Bashkara glacier snout, which is covered by abundant surface debris. For this reason, in our opinion, lake level fluctuations are driven both by meteo-glaciological factors (air temperature, precipitation, snow and ice melting) and by water exchange in the lake-glacier system, which includes such processes as water accumulation in the glacier, filling of englacial cavities with water at the beginning of the ablation season and water release from the glacier in a later period. This may be a mechanism similar to that on South Cascade Glacier (USA) (Tangborn

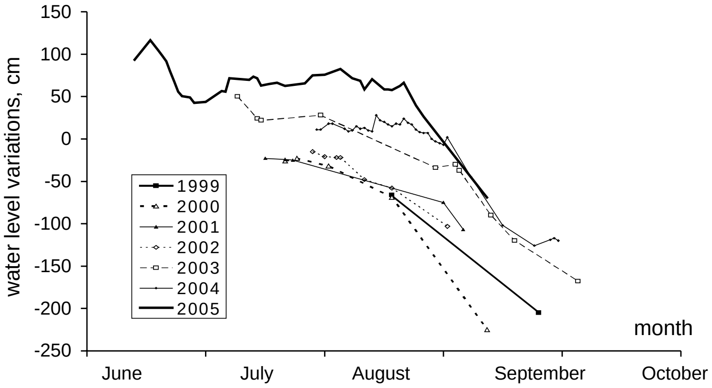

Figure 3. Lake Bashkara water level dynamics during warm periods in 1999-2005. Zero level refers to the zero mark on the permanent level gauge.

et al. 1975), which, like Bashkara, is a warm glacier, and where meltwater accumulated within glacier early during the ablation season and later released.

In 1999-2005 we observed a clear tendency for an interannual rise of Lake Bashkara (Fig. 3). Up to 2002 the level rose insignificantly, but in the cool and rainy summer of 2003 the lake level was 50 cm higher than in 2002. This trend continued and in 2005 the level was about 100 cm higher than five years earlier. We hypothesize that this tendency is a result of changes in the englacial and subglacial drainage system.

3.1.2 *Changes in lake areas and volumes*

We observe that Lake Bashkara is quasi-stable whereas Lake Lapa is drastically expanding. Area and volume of Lake Bashkara are driven mainly by level fluctuations and vary within 60,000-70,000 m^2 and 675,000-800,000 m^3. Below the zero mark on the permanent level gauge, the volume varies annually within a range of 750,000-790,000 m^3 which, we note, is within the measurement accuracy. The maximum measured depth (34 m) in the centre of the lake (Fig. 4). is also stable, so the lake bed relief is assumed stable during the observation period.

Dynamics of Lake Lapa area and volume is presented in Fig. 5a. In 2001-2006 the lake area increased three-fold and the volume multiplied by a factor of five. The process is driven by the glacier terminus retreating from the eastern lake shore. The eastern part of the lake has maximum depths and features the most rapid shore recession (Figs. 5b & 6). The most intensive volume expansion was observed in 2002-003 due to a depth increase and in 2003-2004 due to a notable enlargement of deep areas. In 2005 volumetric increase slowed due to depth stabilization, but in 2006 it accelerated as the lake merged with a very large thermokarst hole in the glacier. Average lake depth has been reduced due

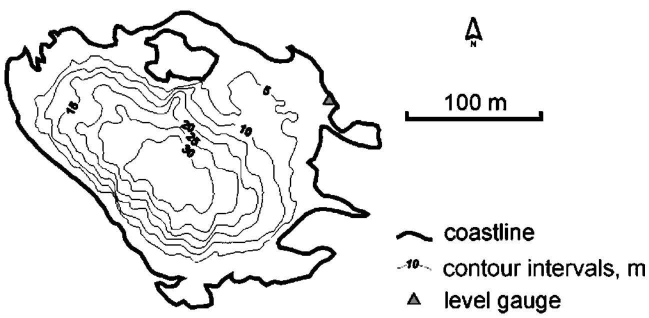

Figure 4. Bathymetric map of Lake Bashkara.

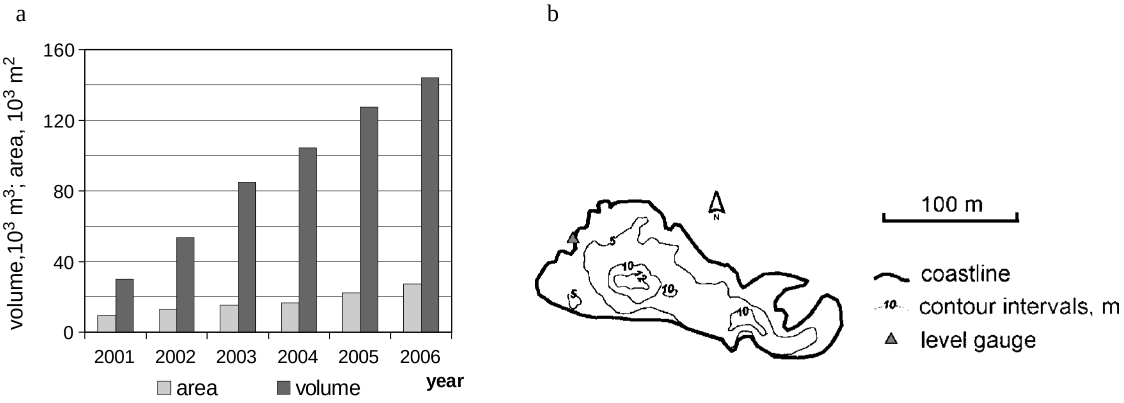

Figure 5. Lake Lapa: a – lake area and volume in 2001-2006; b – bathymetric map in 2006.

to sedimentation on the lake bed. The maximum depth increased two-fold in 2001-2002, was quasi-stable from 2003-2005 and decreased by 1 m in 2005-2006.

In 2001 Lake Mizinchik was comparable to Lake Lapa in area and volume. In summer 2001 transformation of the Bashkara river outlet initiated rapid sedimentation in the lake. Part of the glacier terminus adjacent to Lake Mizinchik has been stable in recent years. As a result the lake in 2004 was only 25% of its size in 2001. In 2005 we could not perform depth sounding of Lake Mizinchik because it was too shallow for measurements. By 2006 Lake Mizinchik had practically disappeared (Fig. 6).

In our opinion, lakes Lapa and Mizinchik are a striking instance of proglacial lake evolution. In the case of stable glacier termini we often observe reduction in lake depths and debris flow hazard. Retreating glacier termini cause lakes to expand (similar cases are presented by Kattelmann 2003, Richardson & Reynolds 2000; O'Connor & Costa 1993) and possibly link to subglacial relief features. In this case lake volume and outburst hazard increase, but at some stage lake depths stop increasing. After this two possible scenarios may occur: GLOF or filling of the lake by sediments.

Development of the Bashkara lake group is closely connected to the Bashkara glacier dynamics. The right part of the snout experiences rapid degradation, terminus retreat, and decrease of ice flow velocities down to zero. As a result active thermokarst processes are observed here. According to our repeat survey data, the surface of the glacier snout lowered by about 10 m on average from 1999-2005. In early summer 2004 a giant thermokarst hole about 40 m deep formed between Lake Bashkara and Lake Lapa about 100 m from Lake Lapa shore. In 2005 this hole was about 50 m deep and about 80 m in diameter. In 2006 it became a gulf of Lake Lapa (Fig. 6f). There are many thermokarst depressions between the lakes, so we predict subsequent narrowing of the ice dam between Lake Bashkara and Lake Lapa. In 2004 the dam width was about 500 m, by 2006 it reduced to about 250 m. This signifies a significant increase of the debris-flow hazard for downstream areas. Bridges in the Adyl-Su River valley, two hotels, and a large camping site hosting up to 500 tourists in summer are all in the danger area. In case of a particularly disastrous outburst, part of the Elbrus settlement with several thousand inhabitants, as well as two bridges on a federal road may be damaged.

3.1.3 *Possible scenario and consequences of lake outburst*

The condition of the ice and moraine dams in the Bashkara area is constantly changing. This makes it difficult to define the scenario of a possible outburst and to calculate its parameters. To assess features of a possible outburst flood, as well as the discharge and volume of the resultant debris flow we applied the method of geographical analogy. We reviewed descriptions of ten GLOFs in Northern Tian Shan and Dzhungarskiy Alatau mountains published in Russian journals *Selevye potoki (Debris flows)* and *Meteorologia i Gidrologiya* (*Meteorology and Hydrology)*. The case which is likely similar to the Bashkara lake group was an outburst of a lake group in the vicinity of the Tushinskiy Glacier of the

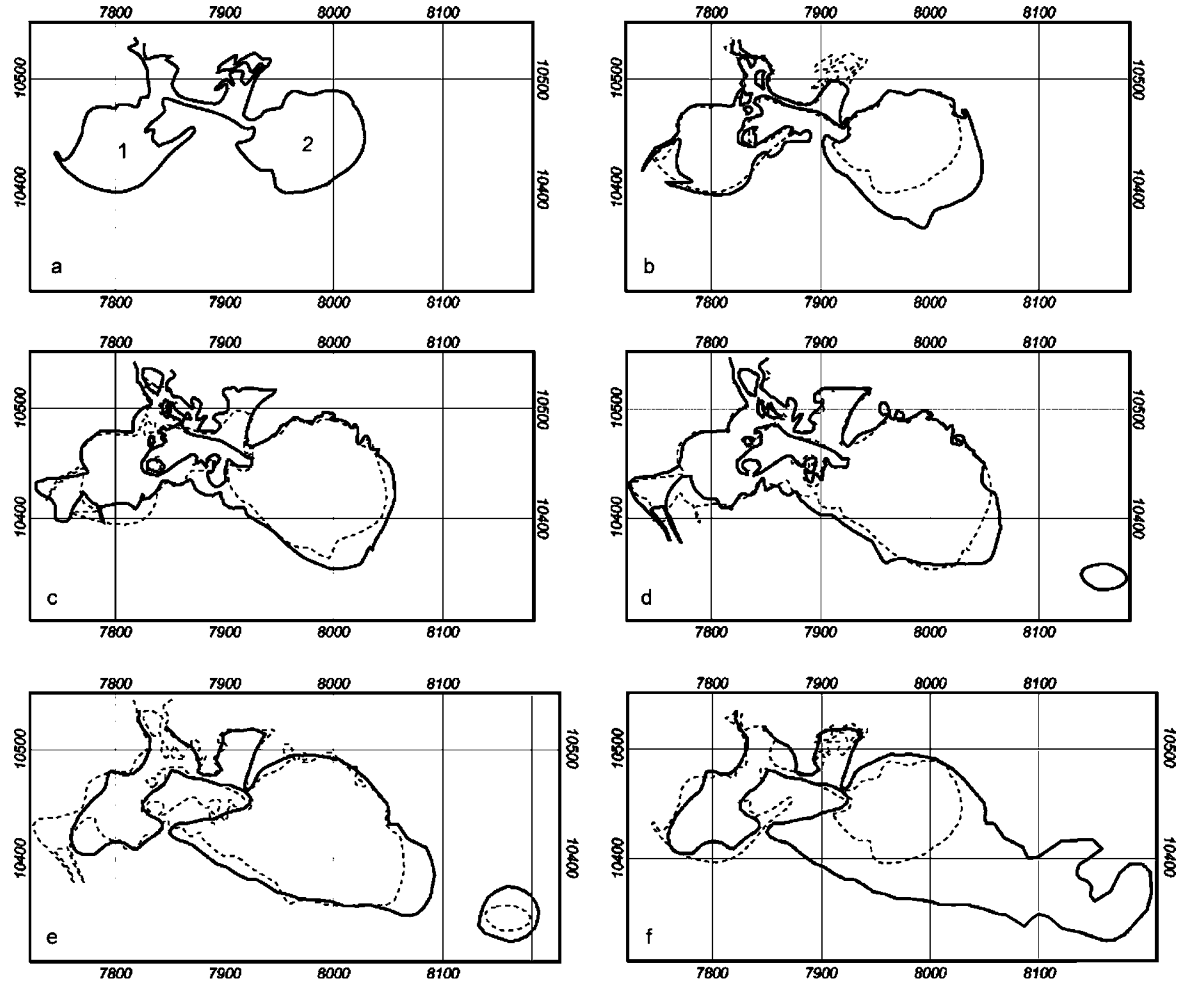

Figure 6. Changes of Lake Lapa and Lake Mizinchik as recorded by repeat geodetic surveys. Lake coastlines: a – in 2001; b – in 2001-2002; c – in 2002-2003; d – in 2003-2004; e – in 2004-2005; f – overall in 2001-2006. Coastlines are shown with solid lines for a later date and with dashed lines for an earlier date. 1 – Lake Mizinchik, 2 – Lake Lapa. Coordinates are given in metres on a local grid.

Dzhungarskiy Alatau range on September 8, 1982 (Tikhomirov & Shevyrtalov 1985). The volume ratio between the large upper lake and the two small lower lakes, and the longitudinal profile of the valley were similar to the Bashkara group. The event also happened on the background of glacier recession. In late August–early September the lake drainage channel was blocked due to ice failure. On September 8, 1982, a break-up of the ice plug led to the lake outburst. The level of the upper lake dropped by 3.5 m, the lower lakes were overrun and their dams rapidly eroded. The outburst had a peak discharge of about 150 m^3/s, which continued for 1.5 hours. Within 1100 m downstream the flood transformed into a debris flow having a peak discharge of about 290 m^3/s. When the debris flow reached a steep moraine terrace (up to 12.5 km path distance from the lakes) it transformed into a disastrous mud-debris flow having a discharge of about 2400 m^3/s and a volume of 2.7 million m^3.

A similar outburst mechanism is likely for the Bashkara lake group. Subglacial drainage channels are in an unstable condition due to thermokarst processes. In case of a channel blockage water will fill englacial cavities in stagnant ice which will then burst. Water release may rapidly lower Lake Bashkara by 5 to 10 m and Lake Lapa may be involved in the resulting GLOF. As a result up to 500,000 m^3 of water may form a flood downstream. Even if the debris dam of Lake Lapa is overrun, flood discharge is not likely to exceed 150 m^3/s. Most likely the GLOF will transform into a debris flow in the area of steeply sloping LIA moraines, as observed during previous bursts in late 1950s.

3.2 *Lakes on the northeastern slope of Mt. Elbrus*

Lakes exist in a large area between Mt. Elbrus east summit (5621 m a.s.l.) and the headwaters of the Malka River (Fig. 1). Modern terrain was mainly formed by Pleistocene and Holocene eruptions of Elbrus volcano and consists of lava ridges dividing depressions filled with moraine, debris flow and lake deposits. The three main glaciers are Mikel-Chiran in the west, and Birdzhaly-Chiran and Chungurchat-Chiran further east. From 1957-1997 Mikel-Chiran receded 270 m and Chungurchat-Chiran receded 570 m (Zolotarev et al. 2005). In this period the area of Mikel-Chiran reduced by 0.23 km^2, while the total area of the other two glaciers reduced by up to 3.5 km^2 mainly due to a drastic retreat of the Birdzhaly-Chiran terminus. According to our estimates, Birdzhaly-Chiran receded more than 850 m since 1957. By now the snout of this glacier has practically disappeared, and a 0.7 km^2 depression between the glacier margin and a lava ridge bounding it on the north is filled with stagnant ice actively decayed by thermokarst. All contemporary lakes below Birdzhaly-Chiran glacier (Fig. 7) are sitting on stagnant glacier ice, and most of them are impounded by stagnant ice, except the lower of the two largest lakes, which is dammed by moraine and lava ridges. Lakes below Mikel-Chiran glacier are impounded by moraine ridges. Two lake outbursts were recorded here earlier: in 1909 a GLOF from a lake at the Birdzhaly-Chiran terminus, which transformed into a debris flow and damaged the Dzhily-Su mineral water resort about 6 km downstream (Gerassimow 1909), and a similar event and damage in 1993 (Yu. G. Il'ichev personal communication).

In summer 2005 we identified 13 glacial lakes in this area (Chernomorets & Tutubalina 2006). A sketch map of the lakes from 1957-2005 illustrates a great expansion in lake numbers and areas (Fig. 7). Due to large changes we analyzed the total lake area. According to our calculations, lake area increased six-fold from 1957 to 2005 and now exceeds 250,000 m^2. The most active lake expansion was observed from 1997-2001, when lake area enlarged from 57,000 m^2 to 235,000 m^2. This can be explained by extremely high summer temperatures, which led to a regional increase of glacier ablation by 30% in 1998-2001 (Popovnin & Petrakov 2005). Thus thawing of stagnant ice had to be very significant on the NE slope of the Mt. Elbrus area when the largest lakes formed.

The largest (southeastern) lake had an area of 89,000 m^2 during our field visit on July 26, 2006. The lake bed was composed of stagnant ice covered with lake, moraine and fluvial deposits. According to our measurements, the volume of this lake was close to 550,000 m^3 with a maximum depths of 17 m. The lake is dammed by Chungurchat-Chiran glacier in the east, and the elevation of this ice dam varies

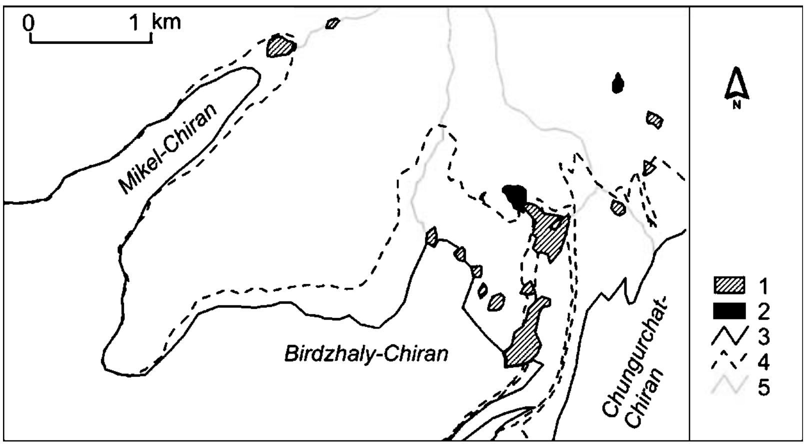

Figure 7. Changes of glacial lakes on the northeastern slope of Mt. Elbrus. 1 – lakes in 2005; 2 – lakes in 1957; 3 – glaciers in 2005; 4 – glaciers in 1957; 5 – rivers in 2005.

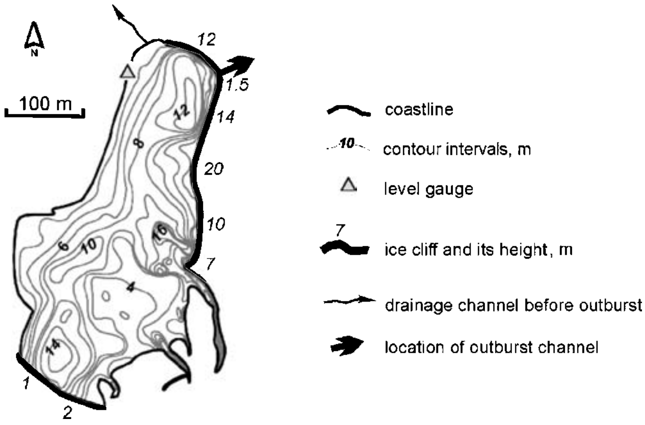

Figure 8. Bathymetric map of the largest glacial lake by the Birdzhaly-Chiran glacier, July 26, 2006.

from 0.8 to 20 m (Fig. 8). It is evident that an outburst through the lowest point of this dam can happen in the near future.

Having extrapolated the ablation vs. altitude ratio of the Djankuat glacier (30 km from this site) we obtained an approximate ablation rate for the ice dam as 5 cm of pure ice per day. Local studies at Djankuat indicate that the existing debris layer of up to 5 cm could reduce the ablation rate by only 10–20% (our assessment based on field observations, and Bozhinskiy et al. 1986). Therefore we hypothesized that an outburst of this lake would likely happen within a month of our measurements. To prevent life loss in the Dzhily-Su resort, we issued warnings to local authorities and the regional office of the Russian Ministry for Emergencies and Disaster Mitigation.

In the early morning hours of August 11, 2006 the lake burst through the ice dam in full accordance with our forecast. Two kilometres downstream, where the flood path became steeper, the resultant GLOF eroded moraine deposits and transformed into a water-rich debris flow. Downstream, due to the varying angle of the flow path, accumulation and erosion areas alternated, and overall the debris flow travelled 10 kilometres. We made detailed field observations in these areas in August 2006, six days after the event, and note that such transformations are well-known (e.g., Kääb et al. 2005; Huggel et al. 2004). The debris flow destroyed buildings and infrastructure of the Dzhily-Su resort in the Birdzhaly-Su river floodplain. There were no casualties because the flow reached the resort at 4am.

Our field measurements established that during the GLOF the lake level dropped by 8.5 metres, and about 400,000 m^3 of water were released. As a result four small lakes (13,000 m^2 in total area) were left in its place (Fig. 9). The lake dam consisted of dense glacier ice. A narrow slit-shaped drainage channel through the dam formed slowly, and traces of numerous intermediate levels implied that the lake water took about a day to drain. For this reason the debris-flow discharge was not as high as it could have been (estimated up to 150 m^3/s by I.B. Seinova, who assessed several valley cross-sections in the field in August 2006). We estimated the total volume of solid material involved in the debris flow at 300,000-350,000 m^3, including 50,000 m^3 deposited directly in the Dzhily-Su resort area. In the case of a more rapid outburst, the debris flow could have been much more disastrous.

The drained lake is currently not dangerous. The greatest GLOF hazard is presently posed by a chain of lakes along the NE tip of the Birdzhaly-Chiran glacier terminus. They are the most dynamic and there are traces of previous outbursts downstream. In a few years the Birdzhaly-Chiran glacier terminus will recess, leading to an increase of lake area and volume. Future outburst debris flows in this area may be more powerful.

3.3 *Other areas*

Our fieldwork and analysis of aerial and satellite imagery for 2004-2006 show that currently there are at least 71 lakes on the north slope of the central Caucasus Range, which are either located in periglacial

a b

Figure 9. The largest glacial lake by the Birdzhaly-Chiran glacier: a) before the outburst, July 26, 2006; b) after the outburst, August 17, 2006.

areas or originate from recent glacial debris flows or glacier disasters. The largest numbers of lakes are located in the upper Malka River valley (see section 3.2). In the Baksan River valley (Fig. 1) we name these lakes Azay, Syltran-Kel, Donguzorun-Kel, Bashkara, Lapa, Mizinchik, and there are two lakes in the Sakashili-Su tributary valley. At least three of these lakes burst in recent decades. In July 2000 after a series of catastrophic glacial debris flows along the Gerkhozhan-Su River the Baksan River was dammed and a temporary lake formed upstream within the town of Tyrnyauz. It was 0.55 km^2 in area and reached depths of up to 12 m. The town was flooded for two months. Eventually a new artificial channel was dug for the Baksan River and the lake was drained. In the headwaters of the Chegem and Cherek Rivers lakes adjoin termini of valley glaciers Zapadny Bashil, Ulluauzna, and Vostochny Shtulu.

Farther east, in North Ossetia, there are lakes near termini of Karaugom, Bartui and Khupnara glaciers, as well as in the headwaters of the Zrug River. A special case is a group of lakes formed after the Kolka Glacier collapse/ice-rock avalanche/debris flow on September 20, 2002, in the Genaldon River valley. In the days after the disaster 13 new lakes were formed. Within a month their total area reached 437,000 m^2 and the total volume exceeded 5 million m^3 (Tutubalina et al. 2003). By 2006 four lakes remained, with a total volume below 250,000 m^3.

4 CONCLUSIONS AND FUTURE RESEARCH

In the last fifty years active formation of glacial lakes has been observed in the Central Caucasus. In key study sites their areas enlarged six-fold at the NE slope of Mt. Elbrus and three-fold in the Adyl-Su River valley. The process of lake expansion is driven by climate change as well as by glacier dynamics. On the NE slope of Mt. Elbrus the most rapid lake expansion took place during an extremely warm period due to intensive thawing of stagnant ice. Bashkara lakes area growth is driven by glacier margin fluctuations; stable expansion was observed only for Lake Lapa due to termini retreat. Fluctuations of glacier dammed lake levels depend on englacial water storages, while the level of openly draining lakes is driven by weather features. The most dangerous lakes are those dammed by glaciers and ice-cored moraines. Although outburst debris flows have been rare in the region, we predict an increase in their frequency in the near future. Rapid change of glacial lakes necessitates annual surveys and lake level observations at dangerous sites.

Our work is focussed on modelling and forecasting consequences of glacial lake outbursts, with an aim of assessing potential debris-flow hazards to populations and infrastructure, and outlining the risk zones. Eventually we aim to create a GIS of glacial lake and debris-flow hazards in the Central

Caucasus, which will give analysis and debris-flow forecast capabilities to researchers and regional decision makers. The outputs of this research should be conveyed in simple form to local populations and visitors in the region.

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