Nat Hazards
DOI 10.1007/s11069-011-9983-5

ORIGINAL PAPER

Monitoring of Bashkara Glacier lakes (Central Caucasus, Russia) and modelling of their potential outburst

D. A. Petrakov · O. V. Tutubalina · A. A. Aleinikov · S. S. Chernomorets · S. G. Evans · V. M. Kidyaeva · I. N. Krylenko · S. V. Norin · M. S. Shakhmina · I. B. Seynova

Received: 10 December 2010 / Accepted: 17 September 2011

Abstract Glacier lakes pose threat to downstream settlements and infrastructure. In recent decades the number and area of lakes have been growing at an accelerating rate due to worldwide glacier shrinkage. In the Russian Caucasus this process is understudied. We present results obtained during a 12-year (1999–2010) continuous field monitoring of the Bashkara proglacial lakes group, which we identified as the place with the highest GLOF risk in the region. Recession of the parent Bashkara Glacier was the main driver of the rapid expansion of the lower Lake Lapa. The upper Lake Bashkara has not been enlarging, but its water level has shown significant inter- and intra-annual fluctuations. The lake outburst probability has increased in recent years, and in 2008 we observed surface overflow over the moraine dam. Taking into account that in the late 1950s lake outbursts at this site led to large-scale glacial debris flows, we have simulated a potential outburst using River and FLO-2D software and carried out hazard zonation. An early warning system has been designed and established at Lake Bashkara, and measures to mitigate risk have been proposed. Rapid change of proglacial lakes requires regular monitoring in 'hot spot' areas where the GLOF hazard is high and is dynamically changing.

Keywords Glacier lakes · Outburst flood · Debris flow · Glacier lake change · GLOF modelling · Hazard assessment · Russian Caucasus

D. A. Petrakov (✉) · O. V. Tutubalina · A. A. Aleinikov · S. S. Chernomorets · V. M. Kidyaeva · I. N. Krylenko · S. V. Norin · M. S. Shakhmina
Faculty of Geography, Lomonosov Moscow State University, Moscow, Russia
e-mail: dpetrakov@gmail.com

A. A. Aleinikov
ScanEx Research and Development Center, Moscow, Russia

S. G. Evans
Department of Earth and Environmental Sciences, University of Waterloo, Waterloo, Canada

I. B. Seynova
University Centre for Engineering Geodynamics and Monitoring, Moscow, Russia

Published online: 13 October 2011

1 Introduction

1.1 Glacial lake outburst floods (GLOFs)

Glacier lake outburst floods (GLOFs) have been known to humankind since Medieval times. The first information about them in the Alpine chronicles refers to the sixteenth century, when a lake outburst from Gietro Glacier killed 140 people (Richard and Gay 2003). Since that time GLOFs have killed 421 people in the Alps (Richard and Gay 2003), about 8,000 in the Andes (summarised from Lliboutry et al. 1977; Morales Arnao 1999) and several hundred in Central Asia (summarised from IPCC 2007; Yafazova 2007).

Some events have led to substantial economic losses, for example Lake Dig Tsho outburst in Nepal 1985 (Richardson and Reynolds 2000). For the majority of mountain glaciers around the world, recent decades have been characterised by an increasingly negative glacier mass balance and consequent glacier shrinkage and termini retreat attributed to rapid climatic warming (Dyurgerov 2003; Oerlemans 2005; Zemp and van Woerden 2008). Projections of future climate indicate that this trend will continue (Raper and Braithwaite 2006; IPCC 2007). The observed and projected reduction in the extent of glacier ice has implications for various geomorphic processes, including accelerating glacier lake formation and expansion (e.g. Stokes et al. 2007). The number, area and volume of hazardous glacier lakes are increasing in mountain areas (e.g. Jansky et al. 2009; Chen et al. 2007; Zemp and van Woerden 2008). This process combined with increasing land use activity in some mountain areas (e.g. Holub and Hübl 2008) could lead to extensive damage and significant life loss in the case of unexpected GLOFs.

Recent studies of glacier lakes have been focussed on lake detection using satellite/aerial imagery, volume versus area and discharge versus volume relations, outburst triggers and mechanisms, dam stability assessment and outburst flood modelling. Simple techniques to determine glacial lake outburst probability (e.g. Reynolds 2003; Huggel et al. 2004) and to assess possible outburst flood run-out distances (e.g. Huggel et al. 2002, 2004) have been proposed. But up to now, the short-term forecast of GLOF as well as the prediction of GLOF inundation area and depth is still a challenge. To obtain new data on glacier lake behaviour in order to improve the short-term outburst forecast, it is necessary to carry out continuous monitoring of glacier lakes that threaten to outburst in the near future. Such monitoring is also important because the hazard potential of particular glacier lakes could change rapidly within just a few years.

1.2 Glacial lake hazards in the Caucasus

In this paper, we report results from our work on hazards associated with glacial lakes in the Caucasus, a highly glaciated mountain range with elevations up to 5,642 m a.s.l. located between the Black Sea and the Caspian Sea. The GLOF hazard has been understudied in the region, despite the occurrence of several GLOF events during the twentieth and twenty-first centuries (Chernomorets et al. 2007; Petrakov et al. 2007; Seinova and Zolotarev 2001). In recent years new data on the current state of glacier lakes and their potential hazard have been obtained, indicating that there are currently up to 70 glacier lakes in the Central Caucasus (Petrakov et al. 2007). Total area of glacier lakes has increased in recent decades (Stokes et al. 2007; Petrakov et al. 2007).

GLOF hazard is a function of potential GLOF magnitude and probability of occurrence (e.g. Huggel et al. 2004). Lake volume and dam type are the main drivers of peak discharge and thus potential GLOF magnitude. GLOF magnitude could be expressed in terms of flood volume, peak discharge and maximum travel distance. The two latter parameters are defined by the dam features and downstream terrain, but are also linked with the first parameter which is dictated by the available lake water volume and is closely connected with the total volume of the lake. So the lake volume could be determined as a confident driver of the GLOF peak discharge (Clague and Mathews 1973; Huggel et al. 2002, 2004) and volume. Most of Central Caucasus lakes are small and have volumes less than 100×10^3 m^3. Probability of GLOF occurrence depends on type and parameters of the lake dam and possible action of the trigger. We note, however, that conventional water GLOFs (sediment concentration low) are quite rare in the Caucasus, and the most common outcome of a GLOF water release is the generation of a glacial debris flow (sediment concentration high) initiated by the passage of outburst flood waters over steep, proximal ice-rich terminal moraines where the flood waters begin to entrain significant volumes of solid material. In the latter case, the final volume of the glacial debris flow may be an order of magnitude greater than the initial outburst volume as a result of entrainment in the debris flow path (Seinova and Zolotarev 2001).

To assess the physical vulnerability of the downstream area, we utilised parameters proposed by Reynolds (2003): lithology, longitudinal gradient of channel, secondary landslide susceptibility and land use. The lithology typical along river channels in the Central Caucasus is granular sediment (Quaternary moraines, talus, alluvium). The longitudinal channel slope gradient in river headwaters is generally higher than 11° and varies between 2° and 11° for rivers with catchment areas over 100 km^2. Landslides are widespread on valley-side slopes. Land is mostly used for cattle grazing. The high mountain area is sparsely populated, infrastructure is not highly developed and is concentrated in the Mt. Elbrus area.

There are five significant lakes/lake groups potentially threatening populated areas; these are located in the Baksan River watershed in the vicinity of Mt. Elbrus (Fig. 1). The largest lake, Syltrankel (Location 1 in Fig. 1), is dammed by rock. The parent glacier has practically disappeared. There is no evidence that rock avalanches threaten the lake, and the possibility of displacement wave formation is considered very low. Thus, it poses a low threat to downstream locations. Glacial lakes on the northern slope of Mt. Elbrus (Location 2 in Fig. 1) pose no hazard after a GLOF in 2006 (Petrakov et al. 2007) due to the small volume of presently remaining water in the lakes. For example, a GLOF with an initial volume of less than 5×10^3 m^3 from one of the lakes occurred here in early August 2007 and transformed to a debris flow but travelled only a few 100 m. In future the situation in this area could change due to continuing lake growth. A lake near Malyi Azau Glacier (Location 3 in Fig. 1) has changed rapidly in recent years. Due to glacier downwasting, its ice dam is degrading. In the early 2000s the outburst probability was low, but it has been increasing since and presently demonstrates a high probability of outburst. However, most probably the GLOF path will be outside populated areas. Lake Donguzorun (Location 4 in Fig. 1) dammed by the Little Ice Age (LIA) moraine of Donguzorun Glacier experiences slow sedimentation. The lake dam is stable, and the outburst possibility is negligible.

The greatest hazard in the region is posed by the Bashkara Lake group (red rectangle in Fig. 1); the Bashkara Lakes are second in volume to Syltrankel but in contrast are dammed by weakening composite moraine/glacier dams. Further, within and near the Bashkara hazard zone there are four alpinist hotels, a large camping site, tourist shelters, restaurants, bridges and the settlement of Elbrus with a total of 5,000 people exposed to the hazard. Debris flows in 1958 and 1959 triggered by GLOFs destroyed part of the area, but there was no tourist infrastructure existing at that time. The lake volume now is much higher than it was 50 years ago, and the state and stability of the lake dams are similar. In

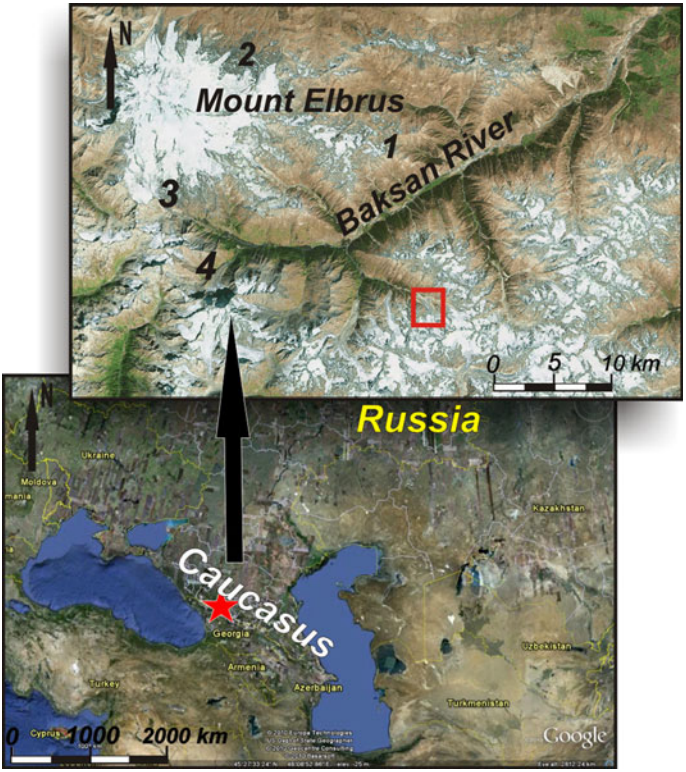


Fig. 1 Location of the study area. *Bottom* extract from the GoogleEarth mosaic, *top* extract from a mosaic of Landsat ETM + satellite images of 9 and 18 August 1999; *1* Lake Syltrankel, *2* lakes on the northern slope of Mt. Elbrus, *3* the lake near Malyi Azau Glacier, *4* Lake Donguzorun. *Red star* shows location of Mt. Elbrus area in the Caucasus. Study area is in the *red rectangle*

combination with high exposure to hazard in the downstream area, we have assessed the Bashkara site as the area with the highest GLOF risk in the Caucasus and therefore selected it as a detailed case study.

The goals of this paper are thus (1) to analyse the results of a 12-year period (1999–2010) of monitoring the Bashkara proglacial lakes to investigate the drivers of their morphometry, area/volume and level fluctuations; (2) to simulate a potential GLOF from Bashkara Lakes using available hydrodynamic models; (3) to describe measures proposed to mitigate GLOF risk; and (4) to describe the design of a low-cost GLOF early warning system which we have been operating at the largest (upper) Lake Bashkara.

2 The Bashkara Lakes

2.1 Bashkara Glacier and its proglacial lakes

The Bashkara group of proglacial lakes have a total area of 100,000 m^2, and a total volume of ca. 1,000,000 m^3 (2010); they are located at 43°12′ N/42°46′ E on the northern slope of the Main Caucasus Range in the upper part of the Adylsu River catchment at the margin of the Bashkara Glacier (Figs. 1, 2). This valley-type glacier is about 4 km in length and 3 km^2 in area. Snow and ice avalanches play an important role in glacier feeding. As a result, about 20% of the total glacier area is debris-covered. At the snout of the glacier debris covers more than half of its area. The Bashkara is a temperate glacier, excluding its uppermost segment located above 3,700 m a.s.l.

The glacier consists of two main flow units. The main trunk of the glacier flows from steep north face of Mt. Ullukara (4,302 m a.s.l.) to the north and turns to the north-west at the snout. A secondary branch flows from a pass between Mt. Bashkara (4,164 m a.s.l.) and Mt. Djantugan (4,012 m a.s.l.) (Figs. 2, 3). This branch descends towards the north-west and flows into the main trunk in the upper part of the snout. During the Little Ice Age (LIA), which started in the Caucasus in the fourteenth century and ended in mid-nineteenth century (Solomina 1999), the glacier snout was divided into two lobes due to the main

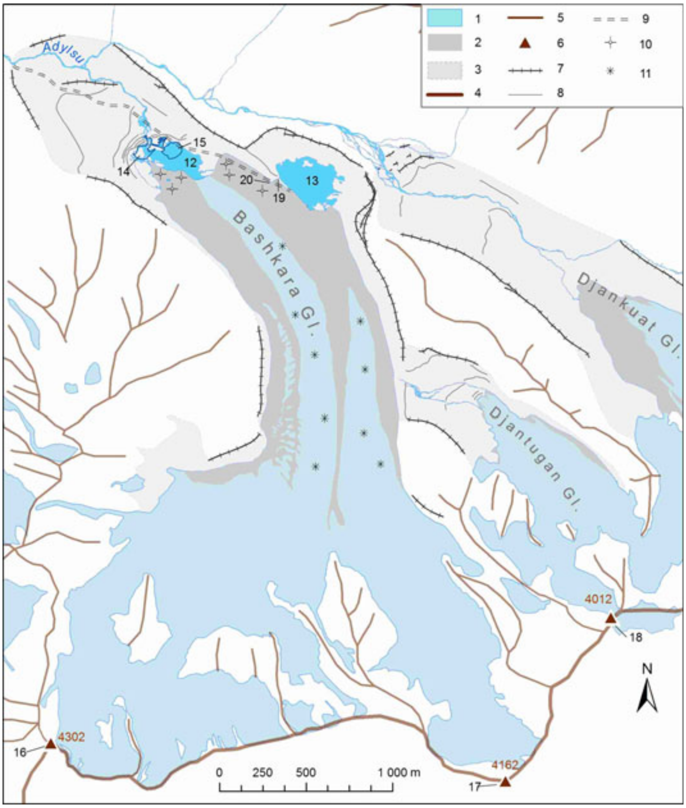


Fig. 2 Sketch map of the study area. *1* glaciers and snow patches, *2* surface debris on glaciers, *3* glacier extent during LIA maximum, *4* Main Caucasus Range, *5* other ridges, *6* main summits (heights are shown in m a.s.l.), *7* LIA moraines, *8* post-LIA moraines, *9* path of the 1958 and 1959 GLOFs, *10* areas of active thermokarst processes, *11* cavities/moulins on glacier surface, *12* Lake Lapa, *13* Lake Bashkara, *14* *shoreline* of Lake Misinchik in 2001, *15* *shoreline* of Lake Lapa in 2001, *16* Mt. Ullukara summit, *17* Mt. Bashkara summit, *18* Mt.Djantugan summit, *19* location of 1958 and 1959 dam failures at the former medial moraine of Bashkara Gl., *20* location of the ice grotto downstream of the current Lake Bashkara dam. The sketch map was compiled using Ikonos imagery of 04.09.2010 (© GeoEye Inc. 2010), provided by R&D Center 'ScanEx', and fieldwork data. Where not specified, *shorelines* of lakes and margins of glaciers are shown for 2010

Fig. 3 Bashkara Lake group. View from the right slope of Adylsu valley towards south. *1* Lake Lapa, *2* Lake Bashkara, *3* Bashkara Glacier, *4* Mt.Ullukara, *5* Mt.Bashkara, *6* Mt.Djantugan. Photograph by E. Klimenko, August 2008

branch obstructing the flow of the secondary branch downstream and deflecting it to the right side of the valley. As a result, a moraine ridge loop was created, where later Lake Bashkara has formed (Location 13 in Fig. 2). The LIA moraine loop surrounding the lake is hypsometrically higher than the lake level by over 50 m; therefore, the lake can only outburst through the Bashkara Glacier, where the minimum ice dam freeboard is only a few metres. On the glacier side, between the Bashkara Glacier and Lake Bashkara (Location 13 in Fig. 2), a former glacier medial moraine is located (Fig. 2). This moraine previously divided the two branches of the glacier and, after stagnation of the secondary branch, developed into a lateral moraine of the main branch (Fig. 2). The height of this moraine above the Bashkara Lake level varies between 2 and 10 m, and it acts as the lake dam. A GLOF burst through this dam in 1958 and 1959 (Kovalyov 1961a, b; Seinova and Zolotarev 2001) and could happen again.

The part of the glacier snout adjacent to Lake Bashkara appears to be stagnant and exhibits active thermokarst processes all the way downglacier to the terminus. The other part of the snout is also debris-covered but is not so prone to thermokarst.

Near the terminus of the main trunk there is another proglacial lake named Lake Lapa (Figs. 2, 3). This lake is dammed by a low (1–2 m high) stadial moraine formed in the late 1980s. Most probably, this moraine contains an ice core as indicated by water pools in surface depressions. Water from Lake Lapa drains over the moraine dam in a surface spillway.

Because Bashkara is a temperate glacier, we expect and we do observe the presence of en- and subglacial drainage channels and cavities. According to eye witnesses, some cavities within the ice are up to 120 m deep (B. Mavlyudov, personal communication). Most of these cavities are located in the upper part of the glacier snout. In the lower part of the snout there are numerous subglacial/englacial channels. A drainage channel opening into Lake Lapa is more than 150 m in length and ca. 2 m in height (N. Kovalenko, personal communication). In the middle part of the glacier snout, immediately downstream of the Lake Bashkara dam, there is a large grotto opening into an englacial channel 4 m in

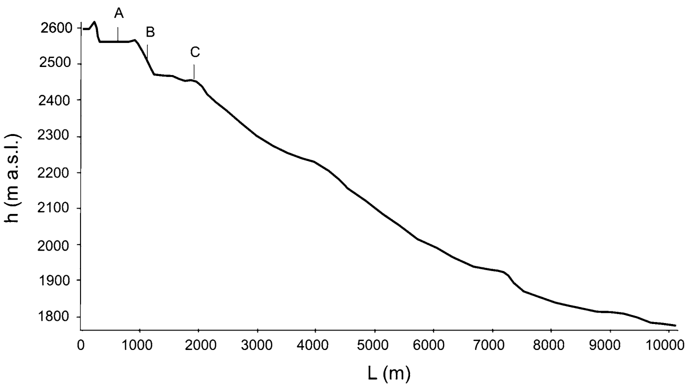


Fig. 4 Longitudinal profile of the Adylsu valley. *A* Lake Bashkara, *B* Bashkara Glacier downstream of Lake Bashkara, *C* escarp of the LIA moraine

diameter (Fig. 4), which then reduces to 1 m diameter at 30 m distance and flows towards Lake Lapa. Water from Lake Bashkara filters through the ice-moraine dam and arrives to this channel at the depth of about 7 m below the surface. This evidence strongly indicates the presence of a well-developed drainage channel system in the Bashkara Glacier snout in which Lake Bashkara and Lake Lapa are interconnected.

2.2 Lake formation and outburst history

In the late 1930s the snout of the secondary glacier branch seemed to be stagnant. This was indicated by supraglacial lake formation: in the late 1930s–early 1940s Lake Bashkara started to form inside the loop due to active thermokarst process. The lake was not shown on a schematic map of the Bashkara Glacier in 1933 (Oreshnikova 1936), but already existed in 1946 as evident on aerial photographs. It was also shown on a 1957 schematic map (Dubinsky and Snegur 1961). At that time the Lake Bashkara area was half the size as it is today (2010). A second smaller lake downstream of the glacier snout is also mentioned in the literature (Dubinsky and Snegur 1961). In August 1958 and 1959 Lake Bashkara burst through its dam. At that time Lake Bashkara was supraglacial and was located on the stagnant ice of the Bashkara flow unit which was hypsometrically higher than in the 2000s, but its dam freeboard was only a few metres. The lake dam was composite and consisted of low moraine ridge sitting on glacier margin. Possible causes of the GLOF in 1958 were overflow of the moraine-ice dam of the lake or lake drainage through a suddenly opening englacial channel in the snout (Kovalyov 1961a, b). The event happened after a period of extreme summer heat. After this GLOF, the level of the lake was lowered by 2 m. The initial volume of water involved in the 1958 GLOF from Lake Bashkara was 60,000 m^3 (Seinova and Zolotarev 2001). The smaller downstream lake located near the current position of Lake Lapa (Fig. 2) was involved in the process and fully drained in the event. A similar event happened in August 1959. The 1958 and 1959 GLOFs resulted in catastrophic glacial debris flows totalling 2 Mm^3 for the two events (Seinova and Zolotarev 2001) that were formed when the floods reached the steep frontal face of LIA terminal moraine (Fig. 4), entrained material and travelled 12 km downstream.

After the 1958–1959 events, the area and volume of Lake Bashkara increased mainly due to bottom ice thawing and continuing glacier retreat. In the 1980s and 1990s the ice dam was 400–500 m wide and the freeboard was 20 m above the lake level; a GLOF from

Bashkara Lake was not expected during this time. The front of the main glacier snout had retreated slowly since the LIA until the end of the 1980s, when new small lakes formed at the terminus of the Bashkara Glacier (Seinova and Zolotarev 2001). In 1991–2001 these lakes continued to grow in area and volume (Chernomorets et al. 2003), but their outburst was hardly possible due to good surface drainage through self-arrested surface spillway channels. The larger eastern lake was named Lake Lapa and the smaller western lake was named Lake Mizinchik (Locations 14, 15 in Fig. 2).

The 1958–1959 GLOFs from Lake Bashkara and consequent glacial debris flows are instructive in forecasting future GLOF hazard in this area. The current geomorphic processes and features of this area are similar to those observed in 1958, as we will demonstrate later in this paper, including degradation of Bashkara Glacier, presence of a smaller lake (Lake Lapa) downstream of Lake Bashkara on the possible GLOF path, and similarities in the lake dam structure. On the basis of historical precedence, and taking into account (1) the continuing lowering and thinning of the Lake Bashkara ice-moraine dam, (2) the formation of englacial drainage channels between Lake Bashkara and Lake Lapa, (3) the presence of a grotto downstream of the most probable outburst point in the dam (Fig. 5) and (4) the rapid growth of Lake Lapa, we can conclude that current situation suggests a growing and serious hazard of a new GLOF.

Fig. 5 **A** View from Lake Bashkara towards the moraine dam and ice grotto. *Note* that the site of overflow in 2008 *1* is at the same place as the dam breach in 1958 and 1959. Bashkara Glacier *2* and the Adylsu valley slope *3* is in the background. Photograph by S.S. Chernomorets, July 2008. **B** View from inside the englacial channel towards the ice grotto near Lake Bashkara. Height of the channel is about 3 m. In May 2008 water filtered through the dam into this channel. At the depth of 11 m below the dam the water stream was clearly visible. Photograph by D.A. Petrakov. **C** View from Bashkara Glacier towards the overflow point in July 2008. Lake Bashkara *4* is in the background. Photograph by S.S. Chernomorets. **D** Stream (about 2 m wide) flowing into the ice grotto and further to the englacial drainage system. Photograph by V.M. Kidyaeva

Vulnerability of the downstream area is now much higher than 50 years ago, due to increased land use by mountaineering hotels and related tourist infrastructure.

3 Data, monitoring methods and analytical techniques

3.1 Monitoring techniques

We have been monitoring the Bashkara proglacial lakes since 1999. The monitoring is based mainly on detailed field observations and measurements; remote sensing on the basis of aerial photographs and satellite images is used as an additional method. Lake 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. In 2008–2009 we obtained lake level data every hour using an automatic level gauge. 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 to 100 m with an estimated error of less than 0.3 m. Sounding points were located along cross-sections spaced at 15–30 m. The horizontal location accuracy was within 5 m. In 2008–2009 we used Lowrance 525 CF two-ray echo sounder which produced geo-referenced echograms. For calculations of lake volumes, average depths and lake bed deformations, we employed Surfer 8.0 and ArcView 3.2 software. In 2007–2008 we also organised experiments to assess seepage intensity through the composite ice/debris dam. Aanderaa Doppler Current Profiler was used to measure the pattern of water currents in Lake Bashkara at different depths, but we did not observe an increase in current velocity near the ice/debris dam. Tracing experiment also did not bring a definite result (dye traces were not recovered below the glacier).

Geodetic surveying of the lakes started in 1999. We have used Zeiss Theo 010B 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). Differential GPS devices (Trimble R3 and Trimble 4600 LS) were used since 2008 for the survey of the downstream area and measurements of dam elevation change. As a result, topographic maps of the study area were compiled in 1999, 2005 and 2007.

3.2 GLOF simulation

Properties of a possible GLOF, such as the inundation area, and flow velocity and depth, were simulated using the River (Belikov and Militeev 1992) and FLO-2D (O'Brien et al. 1993; García et al. 2003) software to delimit hazard zones. The FLO-2D model also provides a capability to calculate debris flow parameters on the basis of the theory of the non-Newtonian viscosity flow. The following information was input for modelling:

- a digital terrain model (DTM) of the Adylsu valley based on a 1:25,000 topographic map surveyed in 1957 and updated for the valley bottom in summer 2008 using a 'stop-and-go' kinematic GPS survey;
- Terra ASTER (2001, 2005, 15 m/pixel) and EROSA (2007, 2 m/pixel) satellite images;

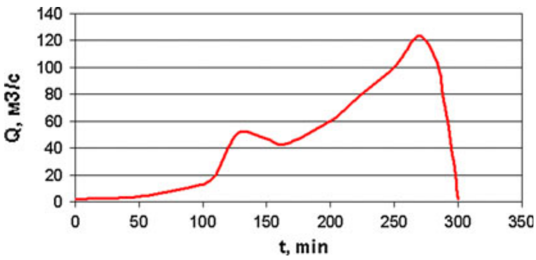


Fig. 6 Bashkara and Lapa lakes potential outburst hydrograph simulated by Gnezdilov et al. (2007) using Vinogradov's (1977) model. The first peak at ca. 125 min. is explained by the drainage of Lake Lapa

- outburst hydrograph simulated by *Sevkavgiprovodkhoz* specialists (Gnezdilov et al. 2007) using Vinogradov's (1977) model. The basis of the Vinogradov's model is an outburst of the mountain lake through an englacial channel. The total volume of the lake which could be potentially involved into the outburst is taken as 700,000 m^3. This corresponds to the upper 12-m layer of water above the lower boundary of water filtration through the moraine dam, at the highest lake level that was observed in summer 2008. Such a water volume would provide a maximum discharge of 123.5 m^3/s, occurring about 4.5 h after the initiation of the outburst. The main outburst hydrograph of Lake Bashkara is overlain by the outburst hydrograph of the downstream Lake Lapa which is considered to be involved in the outburst. Lake Lapa waters produce the bump at ca. 125 min. (Fig. 6). The total volume of Lapa was 166,000 m^3, the maximum discharge is 33 m^3/s, and it occurs about 2 h after the beginning of the outburst (Gnezdilov et al. 2007). Thus, the total water volume of the modelled outburst is 866,000 m^3.

In addition, empirical formulae for outburst discharges (Clague and Mathews 1973) were utilised. These formulae calculate peak discharges 2–3 times lower than the Vinogradov's model, probably because they were constructed for other mountain regions and for open channel failures.

The surface roughness was modelled with Manning roughness coefficient. We have compared simulations with different values of Manning roughness coefficient n (0.05, 0.07, 0.1), which are typical of mountain rivers (Chow 1959) to assess model sensitivity to surface roughness.

For the case of the debris flow simulation in FLO-2D, we used a 30% debris/mud concentration value and empirical coefficients $\alpha_1 = 0.1$, $\beta_1 = 20$, $\alpha_2 = 0.005$, $\beta_2 = 20$ for calculation of viscosity and yield stress, which are computed in the model as an exponential function of the volumetric sediment concentration (O'Brien et al. 1993), according to recommendations in the model manual (FLO-2D 2009).

4 Results

4.1 Lake level fluctuation

Water level in a moraine or glacier-dammed glacial lake without surface drainage is one of the most important indicators of its short-term outburst hazard. Lake Lapa is drained by a well-developed surface run-off channel, so the water level fluctuations are not high. During summer the lake level varies within a range of 10–15 cm, while the seasonal amplitude does not exceed 30 cm. The level of Lake Lapa is also stable at the inter-annual scale.

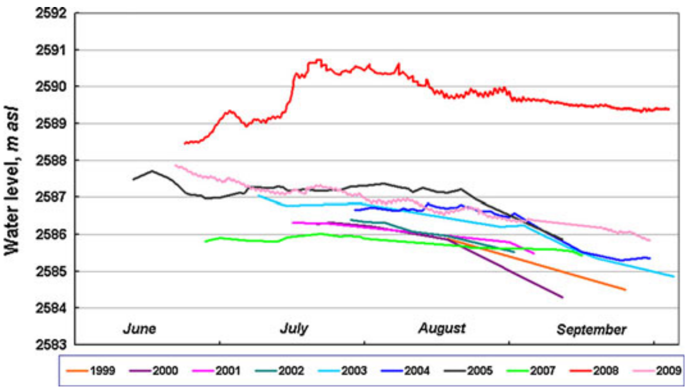


Fig. 7 Lake Bashkara water level fluctuations during warm periods in 1999–2009, m a.s.l

For Lake Bashkara the situation is different, as it has no evident surface drainage. Water draining through the moraine dam concentrates in the ice grotto located 30 m downstream of the possible dam overflow point (Fig. 5). This is most probably not the only drainage point downstream of the lake. The intra-annual water level fluctuations in 2001–2007 were about 150–200 cm, with the highest level usually observed in late June–early July (Fig. 7). After this period, the water level would go slightly down and remain quasi-stable until late summer. At the end of August–beginning of September, the lake level would decrease rapidly to a minimum at the end of the ablation period. During the snow accumulation period (October–May) the lake level is low and quasi-stable. In 1999–2005 we observed a clear tendency for an inter-annual rise in the level of Lake Bashkara (Fig. 7). 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 5 years earlier (Fig. 7). In 2005–2007 we did not observe the inter-annual rise of water level in Lake Bashkara but in 2008 it was 200 cm above the previous maximum (Fig. 7). During the summer of 2008 the level rise was about 400 cm, the level growth continued until 2 July and after a short period of stabilisation (July 2–July 13) for 4 days more. The maximum rate of the daily growth was over 70 cm (Fig. 7), which corresponds to the increase of 45,500 m^3 in water volume. A surface drainage channel from Lake Bashkara did not exist before 2008. Before this, the lake water filtered through englacial channels and cavities in the stagnant part of the Bashkara Glacier snout, which is covered by thick surface debris. In July 2008, however, an overflow through the ice-cored moraine dam into the englacial drainage system (Fig. 5) began due to the lake level increase, leading to alarm in the local region downstream and to intensified monitoring measures.

During the cold and rainy summer of 2009 the water level was 200 cm below the 2008 maximum level (Fig. 7).

4.2 Change in the Bashkara Glacier

Development of the Bashkara Lake group is closely linked to Bashkara Glacier change. The right branch of the snout exhibits rapid ice loss, terminal retreat (Fig. 8) and decrease in ice flow velocities down to zero; active thermokarst processes are observed here. According to our repeat survey data, the surface of the glacier snout lowered by about 1.7 m per year in the period 1999–2005 and 1.4 m per year in 2005–2007. As a result,

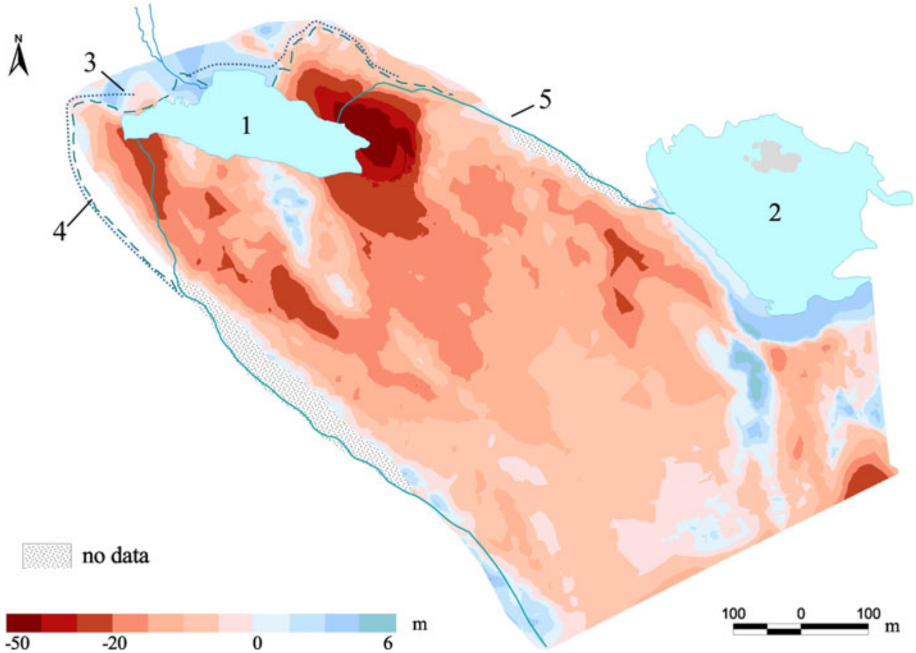


Fig. 8 Change in surface elevation on Bashkara Glacier snout in 1999–2007. *1* Lake Lapa, *2* Lake Bashkara, *3* Bashkara Glacier margin in 1990, *4* Bashkara Glacier margin in 1999, *5* Bashkara Glacier margin in 2007. *Shorelines* of lakes are shown for 2007

mean surface elevation of Bashkara Glacier snout was lowered by 13 m in 1999–2007, but in some areas, surface lowering was ca. 50 m. In the early summer of 2004, a giant thermokarst hole about 40 m deep formed between Lake Bashkara and Lake Lapa, about 100 m from the Lake Lapa shoreline. In 2005 this depression was about 50 m deep and about 80 m in diameter. In 2006 it became a gulf of Lake Lapa (Fig. 9). We identified small snout surface uplift in areas with thick debris cover and in the upper part of glacier snout. Possible causes of this uplift are presented in the Discussion section below. In 1999–2007 the glacier terminus retreated first with the rate of metres per year (left part near the centreline) and later of tens of metres per year (in the vicinity of Lake Lapa) with some acceleration over time. We observed formation of a chain of thermokarst depressions between Bashkara and Lapa lakes, while surface lowering along this chain of surface features was more than average, hinting at the possible presence of an englacial channel below the depressions. The thermokarst processes accelerate the surface lowering and therefore weaken the glacier snout which lies downstream of the moraine dam of Lake Bashkara (Fig. 8). An ice grotto, which formed on the snout surface in 2007 and has been receiving water from Lake Bashkara, appears to be part of this thermokarst chain. This grotto is increasing in size due to thermal erosion by warm (ca. +8 to 10°C) lake water draining through the moraine dam. The distance between Bashkara and Lapa lakes decreases due to the active expansion of the Lake Lapa. Currently (2010), this distance is about 400 m, which is 250 m less than in 1999. The ice dam height above the level of Lake Bashkara (i.e. the freeboard) was about 10 m in 2007 in comparison with 25 m in 1999.

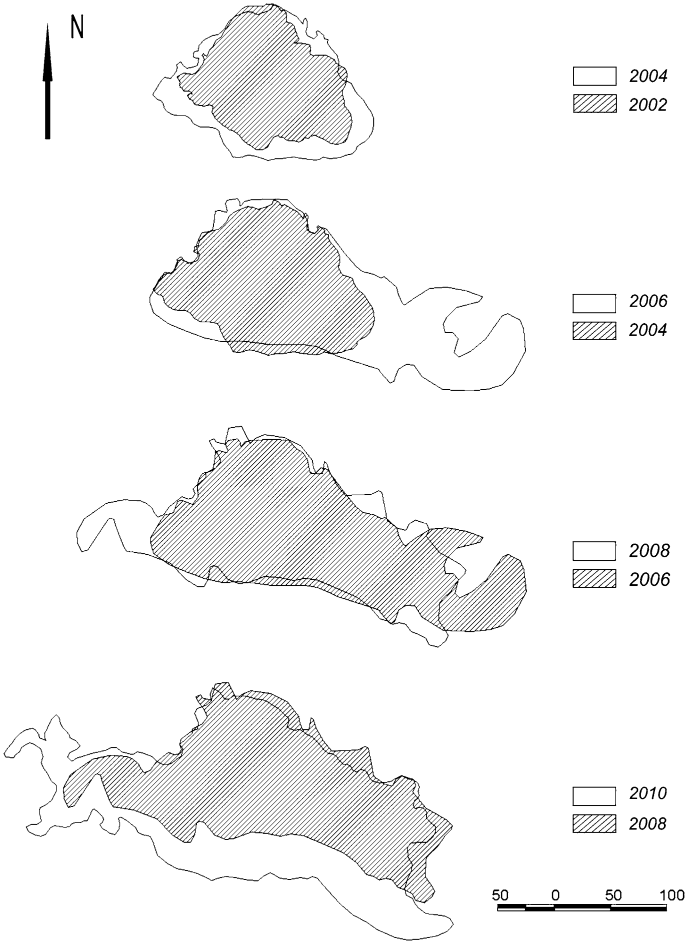


Fig. 9 Changes of Lake Lapa *shoreline* in 2002–2010

4.3 Lake area and volume change

We observed that in the period 2001–2009 the area of Lake Bashkara was nearly constant whereas Lake Lapa rapidly expanded. The area and volume of Lake Bashkara are driven mainly by lake level fluctuations and vary between 60,000–85,000 and 675,000–1,000,000 m^3, respectively. Below the zero mark on the permanent level gauge, in 2001–2009 the volume varied annually within a range of 750,000–790,000 m^3 which, we note, is within the measurement accuracy. The maximum measured depth (36 m in 2008) is in the centre of the lake (Fig. 10), the deepest zone stretches along the border with the glacier ice. The lake bed relief was stable during the observation period.

The change in the area and volume of Lake Lapa is shown in Fig. 11. In 2001–2006 the lake area increased by 50% and the volume increased by 150%. This enlargement process is driven by the glacier terminus retreating from the southern lake margin. The south-western part of the lake has the maximum depth, whereas the south-eastern margin has

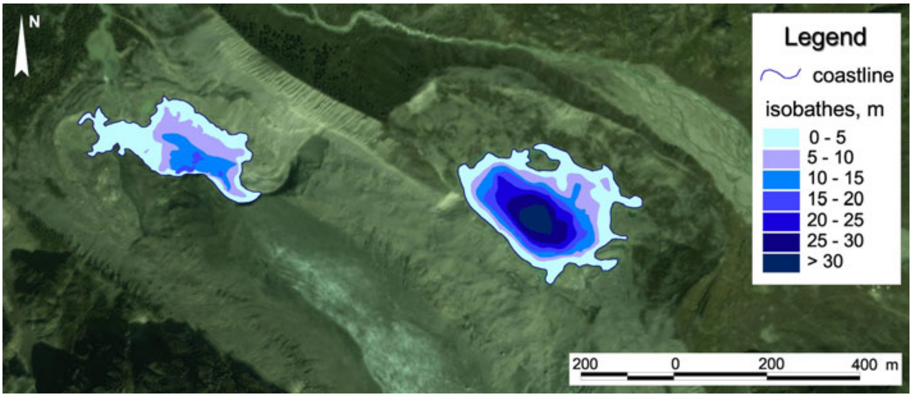


Fig. 10 Bathymetric map of Lake Bashkara in 2008 and Lake Lapa in 2010. *Background* Ikonos imagery of 04.09.2010 (© GeoEye Inc. 2010) provided by R&D Center 'ScanEx'

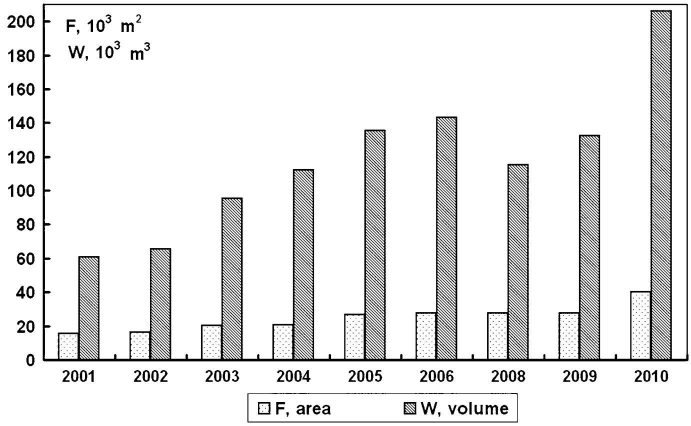


Fig. 11 Lake Lapa area and volume change in 2001–2010

shown the most rapid expansion (Figs. 9, 10). The volume increase was observed in 2002–2003 due to thawing of the icy bottom and consequent depth growth and in 2003–2004 due to a notable enlargement of deep areas. In 2005–2006 the volumetric increase slowed down due to depth stabilisation, despite the fact that in 2006 the lake merged with a large thermokarst hole in the glacier (Fig. 9). In 2008 the Lake Lapa area was close to the lake area in 2006, but its volume decreased by 20% due to change in englacial/subglacial drainage system and deposition of fluvioglacial sediments on the lake bed (Fig. 11). In 2008–2010 the lake continued to expand upstream in the south-western direction (Fig. 9). The lake volume increased by 50% due to the area enlargement and water depth growth (Fig. 11).

In 1999–2001 Lake Mizinchik near Bashkara Glacier terminus (Location 14 in Fig. 2) was comparable to Lake Lapa in area and volume. In 2001 its area and volume were 6,000 m^2 and 30,000 m^3, respectively. Part of the glacier terminus adjacent to Lake Mizinchik has been stable during the first years of the twenty-first century (Fig. 8). In summer

2001 transformation of the Bashkara River outlet initiated rapid sedimentation in the lake. As a result, the lake in 2004 was only 25% of its area 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 due to sedimentation. Now the area of former Lake Mizinchik is a sandur partially covered by shallow water of the western gulf of Lake Lapa (Fig. 9).

4.4 GLOF modelling

Our simulations of GLOFs from the Bashkara Lakes were carried out to produce the following output parameters: flow velocity and depth, inundation area and hazard zonation (Figs. 12, 13). We have utilised three models, including two water flood models using River and FLO-2D and one debris flow model using FLO-2D. We have no precise data about the flow parameters of the previous debris flows, which could have been useful for model calibration; only some data on the extent of the debris flow materials in the Adylsu River valley are available. The calculated inundation zone of both flood and debris flow differs only slightly from the inundation zone of the previous debris flows in 1958 and 1959, because the inundation area is limited by steep slopes of the valley. For the same reason we can see that even a considerable discharge growth and changing model parameters do not lead to flooding of these steep slopes and only lead to a change in flow velocities and depths. For example, if the initial discharge values of a GLOF are increased from 100 to 200 m^3/s, the maximum water depth in the inundated zone calculated with the River model increases from 6 to 7 m, the flow velocity increases from 8 to 10 m/s while the inundated area increases by less than 5%. The inundation areas calculated using the two

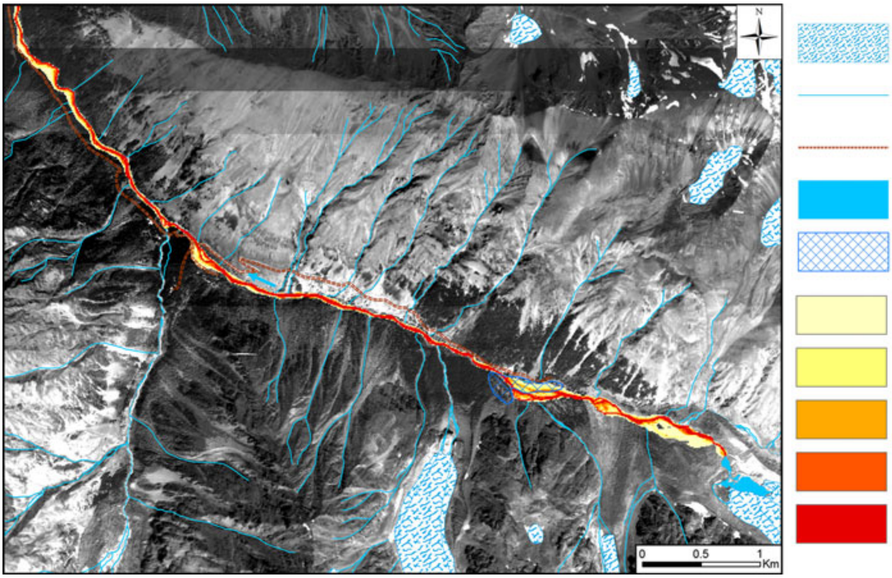
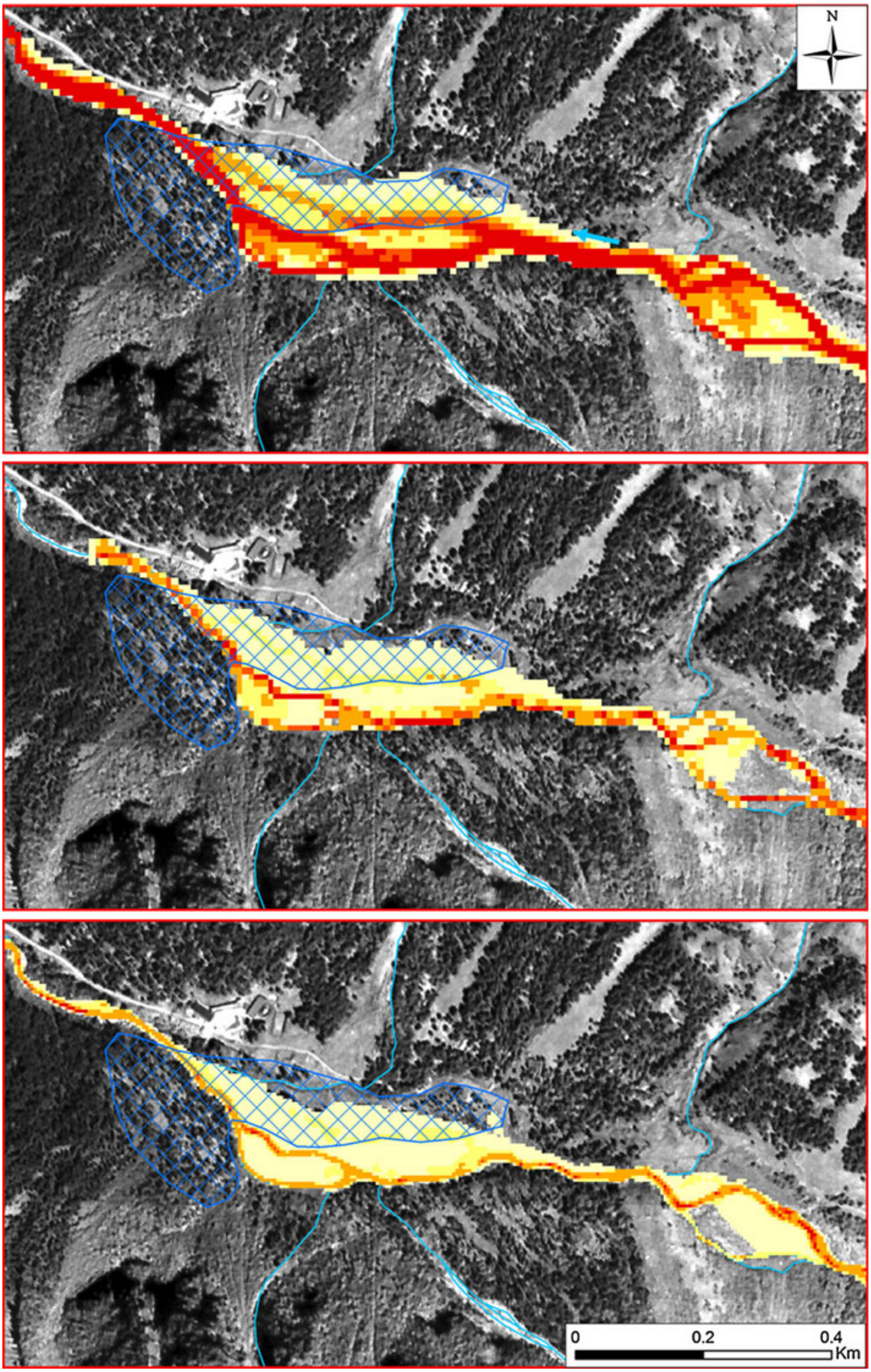


Fig. 12 Hazard zonation in Adylsu valley for potential outburst of Lake Bashkara using FLO-2D model, debris flow scenario. *a* glaciers, *b* rivers, *c* roads, *d* lakes, *e* camping area; hazard: *1* minimal, *2* low, *3* average, *4* high, *5* very high. *Background* EROS A satellite image, 20 July 2007, 2 m/pixel (©ImageSat Intl. 2007, provided by R&D Center 'ScanEx')


N
0
0.2
0.4
Km

◀ **Fig. 13** Hazard zonation in Djantugan Hotel and campsite area for potential outburst of Lake Bashkara using different models and scenario: *top*—FLO-2D model, debris flow scenario; *centre*—FLO-2D model, water flood scenario; *bottom*: River model, water flood scenario. *Legend* and *background* image are the same as in Fig. 12

flood models also differ slightly. The River model gives a higher flow depth than the FLO-2D, whereas the flow velocity is higher for FLO-2D. The River model identifies the main stream in the river bed and a clear distinguished stream on the floodplain, while FLO-2D defines a river bed stream and the shallow water movement through floodplain (Fig. 13). The River simulation portrays narrow flow channels more accurately due to channel-adapted special non-linear grid, while FLO-2D shows the flow in a more general way.

Taking into account that the most likely GLOF scenario is the transformation of the flood wave into a glacial debris flow over the steep (13°–14°) face of the Bashkara Glacier LIA terminal moraine, we focus here on the results of debris flow modelling. This scenario is the most hazardous and has historical precedents in 1958 and 1959. For debris flow simulation we assume that flow density will be ca. 1,800 kg/m^3, typical of non-viscous debris flows in the Caucasus (Vinogradov 1977). Application of a debris flow simulation leads to some increase in inundation area and depth (up to 1 m) in comparison with water flood simulations.

In the case of a GLOF, the debris flow/flood wave would move along the Adylsu River valley quite quickly. The peak of the flood, according to the simulation, should reach the river mouth (8 km away from the source) in 30 min and the Djantugan Hotel and mountaineer campground in 15 min. The flow wave would be the highest (up to 9 m) in the narrow and steep parts of the valley along the river channel. In these sites the velocity of debris flow could reach 13 m/s, within floodplain/terraces the flow speed would be up to 1.5 m/s and the inundation depth up to 1.5 m. In narrow parts of the valley debris flow width would be up to 20–30 m, while an increase in the flow discharge would lead to a negligible increase in the flow width (Fig. 13). In wide parts of the valley the flow width can reach 150 m. The Djantugan Hotel and Ochag Shelter are located outside of the hazard zone, but the protective dam near the Elbrus Alpinist Hotel could be destroyed by the debris flow. Part of the campsite opposite to Djantugan Hotel is in the hazardous area (Fig. 13). The hazard zonation has been made for the Adylsu River valley using the flood hazard criteria applied by Russian Ministry of Emergencies (EMERCOM). We have chosen these criteria because EMERCOM is the principal end-user of our modelling. These criteria are based on impact forces, type and material of constructions within the impact area. The impact force of a debris flow is much greater that of a water flood; we therefore take this difference into account by applying a correction to the flow density (we replace the flow density of 1,000 kg/m^3 for water by 1,800 kg/m^{3}for debris flow (Vinogradov 1977)). Most of the inundated area could be classified as a zone with minimal to low hazard (Figs. 12, 13); this means washout of tents. At the campsite near Djantugan Hotel there are areas with moderate hazard, meaning partial destruction of wooden buildings. Near the river channel the high and very high hazard prevails, meaning that permanent concrete houses and bridges could be completely destroyed.

4.5 Mitigation and early warning system

To mitigate the risk of a GLOF at Bashkara, several measures were proposed and realised in collaboration with EMERCOM. The local population were informed about the GLOF hazard in the valley. To inform tourists and mountaineers about the GLOF hazard, four warning posters were established on the road near camping grounds and on the trail. Local administration and EMERCOM of Kabardino-Balkaria Republic regularly received data on Lake Bashkara water levels and the current GLOF hazard.

We have designed an early warning system especially for Lake Bashkara and have operated it since 2008. It contains an automatic level gauge, a data logger, a transmitter–receiver system based on radio modems and a buzzer. We have selected radio modem communication, because a GSM modem does not provide reliable connection due to the unstable cellular network signal in the Bashkara Lake depression, while a satellite modem requires greater expense and power supplies. The early warning system is operating in the period from June to the end of September, a period when GLOFs are observed in the Caucasus. The system console is located at Djankuat Glacier scientific station within a few hundred m from the lake. Data on lake level are available on a console display; a buzzer switches on in the case of a rapid level drop. There were no real alarms or false alarms during the operating period. To exclude false alarms we propose the following algorithm. In case of an alarm, a qualified observer from the station should call EMERCOM immediately (1) and check the situation visually (2). Action (2) will require 10–15 min. After this the observer should make one more control call (3) to confirm or cancel the alarm. In case of the real alarm EMERCOM would organise further actions to warn local stakeholders, hotel administrations, tourists, etc. Although the first wave (as described in Sect. 4.4) would reach the Djantugan Hotel and the vulnerable campsite in 15 min, we note that the main and significant part of the outburst is likely to happen within a few hours, due to the gradual enlargement of the englacial grotto through thermal erosion of the dam. In this case the early warning system should provide enough time to inform people about the threat and to organise evacuation from the hazardous sites.

5 Discussion

5.1 The glacier lake hazard system

A strong summer warming has been observed in the Central Caucasus in the last 40 years. Since the end of the 1960s, the warm period (June–September) temperatures have been increasing with a rate of 0.03°C per year (Petrakov 2009). Increase in cold period (October–May) precipitation up to 1% per year (Petrakov 2009) did not compensate glacier ice loss caused by increasing ablation (Shahgedanova et al. 2007). As a result, the vast majority of glaciers in the Central Caucasus have retreated in 1985–2000 (Stokes et al. 2006) and continue to retreat as indicated by our field observations. The retreat of Caucasian glaciers is accompanied by an increase in their debris cover (Stokes et al. 2007). Moraines can serve as dams for glacier run-off and lead to the formation of proglacial lakes. Stokes et al. (2007) reported that cumulative surface area of glacier lakes increased by 57% in 1985–2000 for part of the Central Caucasus. According to our data, in 1957–2007 in the Mt. Elbrus region glacier lake area increased by 200%. Glacier downwasting seems to be the major factor in the appearance and expansion of proglacial lakes in the Caucasus. This is typical of the Adylsu valley, where Bashkara Glacier demonstrates terminus retreat and snout thinning.

Both processes are driven by glacier mass turnover and climate conditions, so they were not uniform during 1999–2007. Deceleration of Bashkara Glacier snout lowering in 2005–2007 in comparison with 1999–2005 could be explained by glacier response to the positive mass balance registered on Caucasian glaciers in 2002–2005 (Haeberli et al. 2005, 2007). We note that cumulative balance on the neighbouring Djankuat Glacier in that period was positive, ca. +1,800 mm. Presently, the Bashkara snout surface lowering could accelerate again as a response to strongly negative mass balance anomalies in 2006–2007.

With regard to the surface uplift at Bashkara Glacier, the elevation change of glacier surface is a function of mass balance and ice flow. On the glacier snout a negative mass balance always leads to surface lowering, whereas the ice flow leads to surface uplift. In case of a stationary glacier the mass balance is equal to the ice flow and thus the glacier surface is stable. Bashkara Glacier is retreating now, so the surface uplift caused by the ice flow does not compensate surface lowering caused by ice thawing. This is illustrated in Fig. 8. Surface uplift in some areas of Bashkara Glacier could be explained by influence of surface debris: in uplifted areas it is thick (more than 0.5 m). Surface debris reduces thawing by 9 times in comparison with clean ice, according to the regional observations of Efremov et al. (2007). We suggest that in these areas, the surface uplift caused by vertical component of ice flow is higher than surface lowering caused by ice thawing. A narrow strip with surface uplift along western Bashkara Lake shore was close to a 'blind spot' of the photogrammetric survey and thus could be a measurement/mapping error. Surface uplift zone near the southern shoreline of Bashkara Lake could be a result of sedimentation caused by alluvial processes (mouth of stream) and slope failures from the lateral moraine.

Retreating and thinning of Bashkara Glacier snout have caused Lapa Lake to expand (similar cases are described by Kattelmann 2003; Richardson and Reynolds 2000; O'Connor and Costa 1993). In the case of glacier retreat, growth potential of proglacial lakes is linked to subglacial terrain features. Most probably, Lapa Lake will continue to increase in volume and extent: the deep region of the lake is in contact with the Bashkara Glacier front. Retreat of Bashkara Glacier here could be partially explained by the influence of Lake Lapa. We observed calving in Lake Lapa many times. The transformation of the englacial/subglacial drainage system can cause temporal lake reduction due to sedimentation even in the case of continuing terminus retreat (see Fig. 11, 2006–2008). In the case of a slow retreating glacier terminus (Lake Mizinchik) we observed reduction in lake depths and volume. After 1999, lakes Lapa and Mizinchik were striking instance of proglacial lake evolution. Change of Bashkara Glacier has caused a significant increase in potential GLOF magnitude from Lake Lapa since 1999. There is also a significant increase in GLOF probability because of the possibility of an overtopping displacement wave generated by calving. However, the change in Bashkara Glacier did not cause weakening of Lapa Lake dam.

Influence of Bashkara Glacier change on Lake Bashkara is another linkage in the Bashkara Lakes glacial hazard system. Lake Bashkara water filters through the moraine dam and further into englacial channels and cavities in the stagnant part of the Bashkara Glacier snout, which is covered by a thick debris layer. We assume that the behaviour of Bashkara Glacier, mostly through the change of the englacial/subglacial drainage system, is the main driver of the long-term level fluctuations at Lake Bashkara, and thus a major factor in the GLOF hazard. Short-term lake level fluctuations are driven both by glacio-meteorological factors (air temperature, precipitation, snow and ice melting) and by water exchange in the lake–glacier system, which includes such processes as (1) water accumulation in the glacier, (2) filling of englacial cavities with water at the beginning of the ablation season and (3) water release from the glacier during a later period. This could be a mechanism similar to that noted on South Cascade Glacier, USA (Tangborn et al. 1975), which, like Bashkara, is a temperate glacier, and where meltwater is accumulated within the glacier early during the ablation season and is later released. Glacier change led to a decrease in moraine dam freeboard down to zero in 2008 and more than 10 m lowering of glacier surface behind the moraine dam. Projection of this trend means that in the next 5–10 years, the glacier surface will descend below the current lake level. These glacier changes have led to a decrease in the Bashkara Lake dam stability and thus an increase in GLOF probability. Parent glacier change (i.e. downwasting and retreat) and consequent change of Bashkara and Lapa lakes caused an increase in GLOF hazard from a low level in 1999 to a medium–high level in 2010 with a tendency for further increase. This situation required recommendations for land users, involving hazard zoning and mitigation measures.

5.2 Modelling the GLOF hazard

Several modelling issues should be discussed. We note that flow depth and inundation area for the modelled GLOF link weakly to the surface roughness coefficient. The differences in maximum flow depths with different coefficient values do not exceed 12%, the differences in maximum flow velocities can exceed 30%, but the inundation area is almost unchanged. This is explained by the local terrain features: the inundation area is limited by steep slopes and even a considerable discharge increase does not lead to flooding of these slopes. This is important in considering risk mitigation. However, the flow velocity shows a close relationship to the Manning roughness coefficient value. In the case of $n = 0.1$, in some sites the flow velocity decreased by 200% in comparison with the simulation using $n = 0.05$. But in some areas we observed a slight increase in flow velocity with surface roughness.

There are several options in the choice of the outburst hydrograph. Our conclusions are based on Vinogradov's (1977) hydrograph which presumes melting of ice in the forming englacial tunnel under the action of a water stream. Another outburst model (Keremkulov and Zukerman, 1985) presumes that a wide englacial channel already exists and there is no thawing inside it. Taking into account the warm water in the upper layers of Lake Bashkara (ca. +8 to 10°C in the summer), Vinogradov's model seems to be more appropriate in our case. We also note that the state of the glacier and lakes has changed dramatically in recent years and can change again. So the selection and calculation of the correct outburst hydrograph is still a challenge.

It is also interesting to compare results of flood simulation using FLO-2D and River models. We input identical data on the valley terrain, surface roughness coefficient and water discharge to both models. The model results were similar, but we note some variations due to different grids used by the models to approximate the modelled flow in the study area. FLO-2D uses a regular rectangular grid with the minimum grid size of 10×10 m for the study area. Further reduction of the grid size was not practical, because computation of the model would take several days. The River model uses an irregular non-linear triangle–quadrilateral grid which better approximates the channel shape. The grid size for the Adylsu valley was 4×8 m, while the floodplain was represented with triangular cells. Therefore, river channels with a small width are described in more detail by the River model. This makes the River model better adapted to small river valleys, but the absence of the debris flow model within River precludes from using it to investigate all possible scenarios for the GLOF from Lake Bashkara.

5.3 GLOF hazard mitigation

The most important issue for the Adylsu valley is the selection of which mitigation measures to take in connection with the risk of a Lake Bashkara outburst. Possible options to mitigate the risk are as follows: to reduce hazard, to reduce vulnerability or both. The

GLOF hazard can be reduced by lowering the lake level or by reinforcing the lake dam. We note that due to local topography and the nature of the dam (the lake is dammed by Bashkara Glacier at the point of possible overflow), such a hazard reduction will be expensive and problematic from an engineering point of view.

For example, Zalikhanov et al. (2009) proposed to mitigate the GLOF hazard by water lowering using an open spillway in the south-eastern part of Lake Bashkara. They based this on the assumption that the LIA moraine 'rises over the lake level by 10–45 m and over the bottom of the neighbouring (right) valley of Djankuat glacier by 50–100 m'. In reality the situation is the opposite. The lake level is about 40 m lower than the surrounding Djankuat valley to the south-east, east and north from the lake. Thus, the proposed project is doubtful technically.

The vulnerability reduction through early warning would be more realistic for the available limited local budget. Advantages are as follows: price (equipment costs less than EUR 3,000), weight of the early warning equipment (less than 15 kg with batteries) and easy maintenance. The disadvantage is the need for an observer to filter false alarms and to call EMERCOM in the case of a real alarm. The early warning system is a cost-efficient solution based on serial devices produced and distributed by JSC 'Geolink'. Technical maintenance requires periodical checking of battery power at the transmitter station. The battery charges from a solar panel so checking is important in the case of long rainy periods (1 week and more), which are, however, quite rare during the Caucasus summer. To raise the reliability of the system in the future, it would be useful to augment this system by a break sensor above the river channel downstream of the glacial lakes. However, such sensor could produce false alarms due to numerous cattle grazing in the valley.

The local community knows about the early warning system and accepts it, but visual check of the situation by the qualified observer in the case of an alarm is still required to prevent false alarms. The system has not yet produced an alarm. Therefore, it has not been fully tested.

We note that the essential factor of the proper operation of early warning is the round-the-clock availability of a qualified observer at the station.

The early warning system would provide the most effective vulnerability reduction, because the most vulnerable area is the unprotected tent campsite opposite the Djantugan Hotel. We also recommend reinforcement of the existing levee near the Elbrus alpinist hotel.

6 Conclusions

Long-term evolution of glacier lakes is driven by climate change and resulting parent glacier behaviour. In the Central Caucasus during recent decades, glacier shrinkage and consequent development of proglacial lakes have been observed. The total area of lakes in the Bashkara Lake group enlarged threefold in the last 50 years (1960–2010). The process has been driven by glacier terminus retreat, ice stagnation and active thermokarst development in the right branch of the Bashkara Glacier snout. Long-term fluctuations of glacier-dammed Lake Bashkara level appear to be driven by the behaviour of parent glacier. Short-term fluctuations of Bashkara and Lapa (surface drainage) Lakes are driven by glacier ablation, liquid precipitation and air temperature. The volume of the proglacial lakes is driven by terminus fluctuations as well as sedimentation. Thus, development of adjacent lakes could be in strong contradiction.

Simulation of a possible GLOF is a useful tool to determine hazard area, but verification of this predictive modelling is extremely important. To adapt the FLO-2D model to Caucasian features, we plan to model the most recent regional GLOF, which occurred in 2006 at the north-eastern flanks of Mt. Elbrus. Results of predictive modelling for Lake Bashkara were provided to local decision makers as well as current estimates of the GLOF hazard. A low-cost early warning system was designed and established at Lake Bashkara. Rapid change of proglacial lakes requires regular monitoring in 'hot spot' areas where the GLOF hazard is high and is dynamically changing.

Acknowledgments We thank U. Kurdanov, V. Popovnin, S. Shagin and A. & Z. Sottaev for help and logistical support; Yu. A. Efremov, Yu. G. Ilyichev, M. M. Khadzhiev, I. V. Malneva, E. V. Zaporozhchenko and E. A. Zolotarev for data and useful discussions. We would like to thank two anonymous reviewers for critical comments which have significantly improved the paper. This study is supported by the Russian Foundation for Basic Research, projects 09-05-00934, 10-05-01127, 08-05-92206 NNSF, NATO Science for Peace Program, project 982143; Russian Leading Science Schools Program, grants 3271.2010.5, 3405.2010.5; and the Russian Scientific Educational Centres Programme, grant 14.740.11.0200.

References

Belikov VV, Militeev AN (1992) Double layer mathematical model of catastrophic floods. Novosibirsk, Computer technologies 1:3:167–174 (in Russian)

Chen X, Cui P, Li Y, Yang Z, Qi Y (2007) Changes in glacial lakes and glaciers of post-1986 in the Poiqu River basin, Nyalam, Xizang (Tibet). Geomorphology 88(3–4):298–311

Chernomorets SS, Tutubalina OV, Aleinikov AA (2003) New mudflow-hazardous lakes at the margin of Bashkara Glacier, central Caucasus. Data Glaciol Stud 95:153–160 (in Russian)

Chernomorets SS, Petrakov DA, Tutubalina OV, Seynova IB, Krylenko IV (2007) Glacial lake outburst at the north-east slope of Mt. Elbrus on 11 August 2006: forecast, event and consequences. Data Glaciol Stud 102:211–215 (in Russian with English abstract)

Chow VT (1959) Open-channel hydraulics. McGraw- Hill Book Co, New York

Clague JJ, Mathews WH (1973) The magnitude of Jökulhlaups. J Glaciol 12:501–504

Dubinsky GP, Snegur IP (1961) Physical geography features of the upper Baksan River valley and meteorological observations at Bashkara Glacier. Data of the Caucasian Expedition within the International Geophysical Year framework, vol 3. Izdatelstvo Kharkovskogo Universiteta, Kharkov, USSR, pp 215–285 (in Russian)

Dyurgerov MB (2003) Mountain and sub-polar glaciers show an increase in sensitivity to climatic warming and intensification of the water cycle. J Hydrol 282(1–4):164–176

Efremov YuV, Panov VD, Lurie PM, Il'ichev YuG, Panova SV, Lutkov DA (2007) Orography, glaciations and climate of Greater Caucasus: an experience of comprehensive characteristics and interactions. Krasnodar, Kuban State University (in Russian)

FLO 2D (2009) Reference Manual. Version 2009. Available at: http://www.flo-2d.com/wp-content/uploads/FLO-2D-Reference-Manual-2009

García R, López JL, Noya M, Bello ME, Bello MT, González N, Paredes G, Vivas MI, O'Brien JS (2003) Hazard mapping for debris flow events in the alluvial fans of northern Venezuela. In: Rickenmann D, Chen C (eds) 3rd Int Conf on Debris-Flow Hazards Mitigation. Davos, Switzerland, September 13–15. Millpress, Davos Rotterdam, pp 589–598

Gelman RN (2004) Calibration of digital cameras. In Knizhnikov Yu F (ed) Digital stereoscopic terrain model: experimental studies. Nauchny Mir, Moscow, pp 189–202 (in Russian)

Gnezdilov YA, Ivashchenko EN, Krasnykh NY (2007) Assessment of hypothetical outburst of Lake Bashkara. Sbornik Trudov OAO Sevkavgiprovodkhoz 17:123–144 (in Russian)

Haeberli W, Noetzli J, Zemp M, Baumann S, Frauenfelder R, Hoelzle M (eds) (2005) Glacier Mass Balance Bulletin No. 8 (2002–2003). IUGG(CCS)/UNEP/UNESCO/WMO. World Glacier Monitoring Service, Zurich

Haeberli W, Hoelzle M, Zemp M (eds) (2007) Glacier Mass Balance Bulletin No. 9 (2004–2005). ICSU(FAGS)/IUGG(IACS)/UNEP/UNESCO/WMO. World Glacier Monitoring Service, University of Zurich

Holub M, Hübl J (2008) Local protection against mountain hazards–state of the art and future needs. Nat Hazards Earth Syst Sci 8:81–99

Huggel C, Kääb A, Haeberli W, Teysseire P, Paul F (2002) Remote sensing based assessment of hazards from glacier lake outbursts: a case study in the Swiss Alps. Can Geotech J 39(2):316–330

Huggel C, Haeberli W, Kääb A, Bieri D, Richardson S (2004) Assessment procedures for glacial hazards in the Swiss Alps. Can Geotech J 41(6):1068–1083

IPCC (2007) Climate change 2007: the physical science basis. In: Solomon S, Qin D, Manning M, Chen Z, Marquis MC, Averyt K, Tignor M, Miller HL (eds) Contribution of Working Group 1 to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Intergovernmental Panel on Climate Change, Cambridge and New York, 996 p

Jansky B, Engel Z, Sobr M, Benes V, Spacek K, Yerokhin S (2009) The evolution of Petrov lake and moraine dam rupture risk (Tien-Shan, Kyrgyzstan). Nat. Hazards 50:83–96

Kattelmann R (2003) Glacial lake outburst floods in the Nepal Himalaya: a manageable hazard? Nat Hazards 28:145–154

Keremkulov VA, Zukerman IG (1985) Model of moraine lake release through grotto. Selevye potoki 9:59–70 (in Russian)

Kovalyov PV (1961a) Debris flows at the north slope of the Central Caucasus. In: Materials of the Caucasus Expedition (on the IGY Programme). Kharkov: Izdatelstvo Kharkovskogo Universiteta, III:149–161 (in Russian)

Kovalyov PV (1961b) Modern glaciation in the Baksan River catchment area. In: Materials of the Caucasus Expedition (on the IGY Programme). Kharkov: Izdatelstvo Kharkovskogo Universiteta, II:3–106 (in Russian)

Lliboutry L, Morales Arnao B, Schneider B (1977) Glaciological problems set by the control of dangerous lakes in Cordillera Blanca, Peru, I. Historical failures of morainic dams, their causes and prevention. J Glaciol 18(79):239–254

Morales Arnao B (1999) Glaciers of Peru. Glacier hazards. In: Satellite image atlas of glaciers of the world. Glaciers of South America. United States Geological Survey Professional Paper 1386-I Available at: http://pubs.usgs.gov/prof/p1386i/peru/hazards.html

O'Brien JS, Julien PY, Fullerton WT (1993) Two-dimensional water flood and mudflow simulation. J Hydraulic Eng 119(2):244–261

O'Connor JE, Costa JE (1993) Geologic and hydrologic hazards in glacierized basins in North America resulting from 19th and 20th century global warming. Nat Hazards 8:121–140

Oerlemans J (2005) Extracting a climate signal from 169 glacier records. Science 308:675–677

Oreshnikova YeI (1936) Studies of glaciers of the Elbrus area in 1932-1933. In: Caucasus. Glacier regions. Proceedings of glaciological expeditions 5: 239–299. Leningrad: Redaktsionno-izdatelskiy otdel TsuEGMS, Leningradskoe otdelenie. (in Russian)

Petrakov DA (2009) Glacier response to climate change in the Central Caucasus. Mitigation of natural hazards in mountain areas. Materials of international conference, Kyrgyz Republic, Bishkek city, 15–18 September 2009. Bishkek: Salam, 202

Petrakov DA, Krylenko IV, Chernomorets SS, Tutubalina OV, Krylenko IN, Shakhmina MS (2007) Debris flow hazard of glacial lakes in the Central Caucasus. In: Rickenmann D, Chen C (eds) 4th Int. Conf. on Debris-Flow Hazards Mitigation, Chengdu, China. Millpress, Rotterdam, pp 703–714

Raper SC, Braithwaite RJ (2006) Low sea level rise projections from mountain glaciers and ice caps under global warming. Nature 439:3131–3133

Reynolds JM (ed) (2003) Development of glacial hazard and risk minimization protocol in rural environment. Report No. R7816, Reynolds Geo-Sciences LTD, UK

Richard D, Gay M (2003) GLACIORISK. Survey and prevention of extreme glaciological hazards in European mountainous regions. EVG1 2000 00512 Final report (01.01.2001–31.12.2003). Avialable at: http://glaciorisk.grenoble.cemagref.fr

Richardson SD, Reynolds JM (2000) An overview of glacial hazards in the Himalayas. Q Int 65(66):31–47

Seinova IB, Zolotarev EA (2001) Glaciers and debris flows in the Elbrus region (evolution of glaciation and debris flow activity). Nauchny Mir, Moscow (in Russian)

Shahgedanova M, Popovnin V, Aleynikov A, Petrakov D, Stokes CR (2007) Long-term Change, Inter-annual, and Intra-seasonal Variability in Climate and Glacier Mass Balance in the Central Greater Caucasus, Russia. Ann Glaciol 46:355–361

Solomina ON (1999) Mountain Glaciation of Northern Eurasia in the Holocene. Moscow, Scientific World (in Russian)

Stokes C, Gurney SD, Shahgedanova M, Popovnin V (2006) Late-20th-century changes in glacier extent in the Caucasus Mountains, Russia/Georgia. J Glaciol 52(176):99–109

Stokes C, Popovnin V, Aleinikov A, Gurney SD, Shahgedanova M (2007) Recent glacier retreat in the Caucasus Mountains, Russia, and associated increase in supraglacial debris cover and supra-/proglacial lake development. Ann Glaciol 46:195–203

Tangborn WV, Krimmel RM, Meier MF (1975) A comparison of glacier mass balance by glaciological, hydrological and mapping methods, South Cascade Glacier, Washington, vol 104. IAHS, AISH Publication, pp 185–196

Vinogradov YB (1977) Glatsialnye proryvnye pavodki i selevye potoki [Glacier lake outburst floods and debris flows]. Gidrometeoizdat, Leningrad (in Russian)

Yafazova RK (2007) Priroda selei Zailiiskogo Alatau. Problemy adaptatsii [Nature of Debris Flows in the Zailiysky Alatau Mountains. Problems of adaptation]. Almaty, (in Russian)

Zalikhanov MCh, Anakhaev KN, Nedugov AN (2009) On Mudflow Hazardous Bashkara Lake. Russ Meteorol Hydrol 34(2):125–127

Zemp M, van Woerden J (eds) (2008) Global glacier changes: facts and figures. UNEP, WGMS