Outburst flood hazard: Case studies from the Tien-Shan Mountains, Kyrgyzstan

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Abstract

More than 2000 of mountain lakes covering more than 0.1 ha exist in a territory of Kyrgyzstan. Nearly 20% of them are dangerous because of instability of lake dams, frequent overflows and melting of buried ice inside the moraine dams. According to the Kyrgyz lake inventory, 328 lakes are at risk of outburst and 12 lakes are considered as actually dangerous. Since 1952 more than 70 disastrous cases of lake outbursts have occurred. The majority of the endangered lakes belong to one of the three genetic types: morainic-glacier, supraglacial and lake dammed by landslides and debris flows. Petrov, Adygine and Koltor lakes were selected and studied in the Tien-Shan Mountains as case studies of the most frequent genetic types of hazardous lakes. Observations were focused on the morphology of the lake basin and the surrounding relief, outflow pattern and processes controlling the development of lake. For the hazard assessment, evolution of glaciers and lakes was reconstructed using historical reports, aerial photographs and satellite images.

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Introduction

An intensive melting of glaciers is observed in the majority of high mountains all over the world. Melting water of glaciers influences changes in hydrological regime of water streams and causes overfilling of high mountain lakes basins. Dams of many lakes are very unstable and they often burst. Mountain lake outburst floods have been reported from the Alps (Haeberli, 1983; Huggel et al., 2002), Karakoram (Hewitt, 1982), Himalayas (Richardson and Reynolds, 2000; Kattelmann, 2003), Tien–Shan (Meiners, 1997; Mayer et al., 2008), Coast Mountains (McKillop and Clague, 2003), Rocky Mountains (Walder and Driedger, 1995; Clague and Evans, 2000) and Andes (Clague and Evans, 1994; Carey, 2008). Whereas inventories in most of these regions contain hundreds of moraine-dammed, landslides and debris-flows-dammed lakes and a lot of systematic information for hazard assessment, only few data exist for the Tien-Shan Mountains in the territory of Kyrgyzstan. According to their development, these lakes may be classified as tectonic, glacier, morainic-glacier, morainic, lakes dammed by a landslide, rockfall or debris flows (Janský et al., 2006). The majority of the endangered Kyrgyz lakes belong to one of the three genetic types: moraine-glacial, supraglacial and lakes dammed by a landslide, rockfall or debris flows (Yerokhin, 2002).

Moraine-glacial lakes develop in moraine depressions after retreat of glaciers. The bottom and the slopes of the lake basins are formed mainly by ice and frozen debris. Water is cumulated on this impermeable material and in summer it warms up to 8–10°C, which causes a melting of frozen material. The lake basin is getting progressively deeper and its volume is increasing to reach dozens to millions of m³. The moraine-glacial lakes are considered as the most dangerous type including 47% of listed Kyrgyz lakes. One of the largest lakes of this type is the Petrov Lake in the Ak-Shiirak massif in the Inner Tien-Shan (Figs. 1 and 2).

Supraglacial lakes develop on the surface of glaciers. Outflow from the lake is either surface or through the underground channels. More rapid bursts occur in case of surface outflow. The most dangerous are supraglacial lakes with periodical filling. They develop in closed depressions with underground outflow where the active basin development is already finished. When underground channels get blocked up, the lake fills quickly and the risk of outburst increases. Lower Adygone Lake in the Kyrgyz Range was studied as a case study of this type of lake.

Lakes dammed by a landslide, rockfall and debris-flows are characterized by a great volume and mostly underground drainage. Lakes can be also drained on the surface, or both types may be combined. Maximum discharge during outburst events may reach hundreds or thousands of m³/s. An example of a lake

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0075-9511/$ - see front matter © 2010 Elsevier GmbH. All rights reserved.
doi:10.1016/j.limno.2009.11.013
the dam formed by a rockfall is the Koltor Lake on the northern slope of the Kyrgyz Range.

Materials and methods

The lakes presented in this paper have been investigated in summer months since 2005. Shorelines of the lakes have been delimited using geodetic total station Leica TCR 705. Systematic depth measurements were made by echosounder with 20 cm resolution. Depth measurements along 29 profiles on Petrov Lake, 19 profiles on Koltor Lake and 15 profiles on Adygine Lake allow for construction of detailed bathymetric maps of the lakes.

The description of lake outburst hazards is based on simple glaciological, geomorphological and hydraulic principles (see Haeberli et al., 1989; Clague and Evans, 1994) and on experience gained from previous events. The hazard assessment follows the procedure proposed by Huggel et al. (2004) using lake volume, probable maximum discharge, volume and travel distance as input characteristics. Five key indicators are defined to which qualitative probability in the range of low, medium and high can be assigned. The overall probability is derived from the highest rated individual indicator (Richardson and Reynolds, 2000).

The evolution of glaciers is outlined considering available documentation. The position of Petrov Lake glacier terminus is reconstructed since 1957 using aerial photographs (1962 and 1988, ~1:47,000 scale) and a QuickBird satellite image (2006). Glacier positions from six periods were digitised into the GIS, enabling a tentative analysis of the glacier terminus fluctuations.

Results and discussion

Petrov Lake

The proglacial lake is situated in the foreground of the Petrov glacier in the Ak-Shirak massive, the Inner Tien-Shan (Fig. 2). The Petrov glacier extends over 69.8 km² and belongs to the largest glacier in the whole River Naryn catchment. The altitude of the lake surface is 3733 m (Table 1). Petrov Lake is formed by two oblong basins separated by shallows and islands based on relics of the central moraine. The northern basin is deeper (70 m) and more extensive than the southern one (21 m; see Fig. 3). Its eastern shore is formed by the calving terminus of the Petrov glacier. The Petrov Lake is dammed by a terminal moraine on its western side (Fig. 4).

The development of the lake since the beginning of the 20th century is presented in Table 2. Historical changes of the lake surface have been described according to expedition reports, maps and aerial photographs. Recent development of the lake in 21st century is documented by field mapping and measurements. The lake surface was extending since the first report presented by

Table 1

<table>
<thead>
<tr>
<th>Morphometric characteristics of Petrov, Koltor, Upper and Lower Adygine lakes.</th>
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<tbody>
<tr>
<td></td>
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<tr>
<td>Altitude (m a.s.l.)</td>
</tr>
<tr>
<td>Area (ha)</td>
</tr>
<tr>
<td>Volume (thous. m³)</td>
</tr>
<tr>
<td>Maximum depth (m)</td>
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<tr>
<td>Mean depth (m)</td>
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<tr>
<td>Perimeter (m)</td>
</tr>
<tr>
<td>Length (m)</td>
</tr>
<tr>
<td>Maximum width (m)</td>
</tr>
</tbody>
</table>

Fig. 3. Bathymetric map of the Petrov Lake based depth measurements from July 2008.
Kaulbars (1875) with the exception of period 1943–1957 when the Petrov glacier front advanced (Davydov, 1927; Sevastianov and Funtikov, 1981). The most intensive increase of the lake surface was observed recently (1995–2006). During this period the lake has reached an area of 3.80 km², which represents a mean annual increase by 92,700 m² (Jansky et al., 2009). Since 2006 the lake surface increased to 4.03 km² in 2009 (mean annual increase by 77,000 m²).

The annual oscillation of the lake surface reflects changes of air temperature. The lake surface begins to increase at the end of April when maximum daily temperatures culminate above the freezing point. The maximum increase of the lake surface occurs in May as mean daily temperatures are positive and snow and ice melting intensifies. The increase of the lake level surface and volume lasts till the end of July. Then a progressive decrease of the lake surface follows with the minimum at the beginning of December (Fig. 5a).

The development of the moraine dam is controlled by the ongoing degradation of buried ice. Ice forms the major part of the moraine and represents the most dynamic part of the dam. Degradation of the ice is accompanied by relief sinking, mass movements and thaw lake formation. According to the amount and activity of the dead ice, it is possible to distinguish four zones in the moraine. These zones have a different rate of impact on the process linked to the ice degradation and geomorphological hazards. The slope declinations on those banks often exceed the critical value, which is connected with a further deepening of the thermocarst lakes (Fig. 6). Narrow strips of dry land between individual lakes are constantly sinking which has caused hydrological connecting of the lakes. An intensive development can be observed within the largest lake in the north-east part of the dam. In comparison with a bathymetric map from 2005, its volume has increased from 745.569 to 775.465 m³ in 2008. The maximum depth of the lake is 21.7 m and its average depth is 8.6 m. This lake cuts deeply into the moraine dam representing the most weakened part of the Petrov Lake dam (Fig. 7).

### Table 2

<table>
<thead>
<tr>
<th>Year</th>
<th>Area (km²)</th>
<th>Annual growth (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1911</td>
<td>0.2–0.3</td>
<td>–</td>
</tr>
<tr>
<td>1947</td>
<td>0.80</td>
<td>15,000–18,000</td>
</tr>
<tr>
<td>1957</td>
<td>0.96</td>
<td>11,000</td>
</tr>
<tr>
<td>1980</td>
<td>1.83</td>
<td>37,600</td>
</tr>
<tr>
<td>1995</td>
<td>2.78</td>
<td>63,000</td>
</tr>
<tr>
<td>2006</td>
<td>3.80</td>
<td>92,700</td>
</tr>
<tr>
<td>2009</td>
<td>4.03</td>
<td>77,000</td>
</tr>
</tbody>
</table>

Fig. 4. Longitudinal profile of the Petrov Lake with the depicted surface in case of outburst (12 times exaggerated).

Fig. 5. Seasonal water level oscillations of Petrov (a), Lower Adygine (b) and Koltor (c) lakes.
The increase of the lake volume along with a weakening of the moraine dam represents permanent risk of moraine failure and lake outburst. In case of a dam rupture in the area of the largest thaw lake about 37 million m$^3$ of water would flow away from Petrov Lake.

The Kumtor River flows out of the lake. It continues to the southeast and, after about 25 km, joins with the Taragai River. The Taragai joins with the Dzasikchi, after another 30 km, and its name changes to the Naryn River. For this entire distance, the rivers flow through wide mountain valleys with an average slope of approximately 1%. Permafrost is found on the flat bottom of the valley. The possible outburst of the lake would primarily threaten the infrastructure of the Kumtor Gold Mine, whose toxic waste dump is located, along with additional infrastructure, about 3 km below the lake's dam. Also municipalities and roads in a sparsely populated area, in the subsequent section of river valley, will be threatened. A dam rupture could cause a water mass of up to 13 m in depth, representing 37 millions m$^3$ of water, i.e. roughly 62% of the lake's total volume, to flood the area. In light of the morphology of the valley, a wide flood wave that would transform as a result of its broad outflow could be expected to form.

**Lower Adygine Lake**

The Lower Adygine Lake is situated on the debris-covered glacier on the northern side of the Kyrgyz Range, the Northern Tien-Shan. The supraglacial lake was formed since the Little Ice Age and it is dammed by a morainic material. The maximal depth of 4.7 m was found in the central part of the lake basin. The lake covers 3390 m$^2$ and has a subsurface outflow (Table 1).

The lake was formed in an about 50-m-deep and 150-m-long thermocarst depression which is probably supplied, beside the surface water, also by subsurface channels. The lake level and volume of lake largely oscillates during the day – approximately between 10,000 and 15,000 m$^3$ (Figs. 5a and 8). The maximum depth is reached in the afternoon. High daily oscillations of the water level are connected with the limited capacity of the draining channels.

The Lake overflowed several times in the past by melting a subsurface gorge through a moraine dam. Drainage events occurred when the area of the lake increased and exceeded an unknown critical area. A progressive warming in the area within 20th century (Dyurgerov, 1995) probably reduced the critical area. The lake drained through a moraine onto the surface of the valley floor within about one day. The main source of water for the lake is the Adygine glacier. The development of the glacier since 1962 is characterized by slow retreat of the glacier terminus with accelerating tendency in the last years (Fig. 9). In case of a further retreat of the glacier, we can expect an increased inflow in the Upper Adygine Lake and after that in the Lower Adygine Lake. According to topographic conditions up to 300,000 m$^3$ of water can collect in the lake basin. A large volume of water will increase the risk of outburst floods which repeatedly formed within 20th century.

The most likely risk is the subsurface outburst of the Lower Adygine Lake, which could happen in the event that the runoff canals are blocked and the lake basin fills up quickly. The danger is increasing due to the emergence of new, small lakes in front of
the glacier’s head and the direct inflow from these small lakes. First, the stream flows below the surface of the moraine complex, for about 1.2 km. It then flows into a narrow valley, which has no developed floodplain. A flood wave can be expected to have great erosive power and to carry away a large amount of accumulated material from the valley’s walls, until the confluence with the Ala-Archa River. The average slope of this section is 22.4%; the area has no permanent settlements. The closest settlement is Kashka-Su Municipality, which is located about 15 km below the confluence with the main current of the Ala-Archa. The valley broadens here and the average slope remains fairly high–4.2%. A dam has been built near Kashka-Su municipality (which lies at the beginning of a massive alluvial fan), from which some of the water is diverted into an irrigation canal. The reservoir is almost completely filled in with dirt. No transformation can be expected due to a flood wave; in contrast, it is more likely that the entire accumulated area would be carried away. Farther along its course, the river flows through fluvial deposits and after 12.8 km it enters the outskirts of Bishkek, where a slope of 3.2% enables the continued transport of material. In this section, the river flows through a relatively densely populated area. Settlements in numerous localities lie directly on the banks of the river.

**Koltor Lake**

The lake is situated in the valley of the Koltor River which drains the northern slope of the Kyrgyz Range. The lake was initially formed as a morainic lake which was subsequently transformed by rockfalls (Yerokhin, 2003). The lake basin has a regular shape corresponding to the valley-type of the lake dammed by both morainic material and mass-movement accumulations. The area, the volume and further hydrographical characteristics of the lake depend on the lake surface level which changes substantially throughout the year. With its surface at an altitude of 2726 m, the lake area in 2005 was 22.15 ha and its volume 1,830,000 m³ with the mean depth of 8.3 m (maximum 14.8 m, Table 1, Fig. 10).

The Koltor Lake was formed as a morainic lake and its basin was probably at first shallow (Yerokhin, 2003). The moraine was then covered by a rockfalls from the left side of the valley increasing the high of the dam and depth of the lake basin. Historical changes of the lake can be assessed using bathymetric measurements made in 1966 (Grigoriev and Frolov, 1966). The lake surface and volume increased slightly until 2005 as well as the maximum depth (Table 3).

The lake is supplied by water from glaciers, seasonal snow cover, rainfall and underground water headsprings. The dominant part of melting glaciers is manifested in the hydrological regime of the lake, both in the seasonal and in the daily cycle. The lake surface level begins to rise at the end of March when snow in the catchment begins to melt. According to Shnitnikov (1975), it rises till the end of April by 3–4 m. The second increase of the water level appears in the middle of June when glaciers in the spring area of the Koltor River melt. After reaching its maximal level in August, the water surface begins to sink in September. The decrease continues up to November when the lake gets covered by ice. At this time, the water surface level is some 8–10 m below the maximum level (Fig. 5 c). The daily hydrological regime of the lake is influenced above all by melting of glaciers. The highest water level is registered during the morning hours, when water which has melted the day before enters the lake with a roughly 20 hours delay.

The lake dam is about 250 m wide and more than 270 m long. The dam consists of consolidated glacial sediments and mass-movement material. The boundary between the moraine and younger landslides is hardly distinguishable. The dam contains unsorted gravelly to boulder material.

The main outflow—subsurface—is situated in the north-western part of the lake. Surface overflow occurs after sudden torrential rains or after intensive melting of iced parts of the valley. Water flowing over the lake dam was observed only rarely in the past. It occurred in 1966, when a 160-m-long, 12–28-m-wide and 4-m-deep erosion furrow was formed at the low side of the dam (Karpov and Tsytserenko, 1966). The dam was then overflowed in July and August 1997 (Yerokhin and Aleshin, 1997) and on the 23rd and 24th of July 2004. The latter case was caused by debris flow which fell into the lake. The dam was overflowed up to the height of about 30 cm above the lowest overflow point and the erosion furrow on its outer side was deepened. The last overflow occurred after an intensive snow melting in July 2006. The water level rose by approximately 1.5 m and during three weeks the volume of water in the lake increased at least by 300,000 m³. During the overflow, water flew into the open canal in the dam.
outburst, would be threatened by a flood wave. Such a wave would reach even the village of Kenbulun in the Chu River Valley, which is nearly 40 km away from the lake. The flood surge would hit incoming roads and destroy bridges and water supply pipes located along the river.

An assessment of hazards related to glacial lake outburst

The assessment procedure for the Petrov Lake is based on the following findings: (a) lake volume $V=60.398 \text{ million m}^3$ (depth measurements in 2008); (b) moraine dam with 50–70% of buried ice; (c) probable maximum discharge $Q_{\text{max}}=74.783 \text{ m}^3/\text{s}$ ($Q_{\text{max}}=2 \text{ V/t}$ according to Huggel et al., 2002); (d) abundant sediments along the steep flow path; (e) probable maximum volume of the debris flow of 480,000 m$^3$ (750 m$^3$/m of sediment per 400-m-long section of river channel and 200 m$^3$/m per 900-m-long section); (f) probable maximum travel distance of the debris flow of 3200 m (an average slope of approximately 3% and rectangular-shaped channel cross section of 3 m depth and 50 m width).

The following parameters were used for the assessment of Lower Adygine Lake: (a) lake volume $V=6290 \text{ m}^3$ (depth measurements in 2006); (b) moraine dam with buried ice; (c) probable maximum discharge $Q_{\text{max}}=12.58 \text{ m}^3/\text{s}$; (d) abundant sediment along the steep flow path; (e) probable maximum volume of the debris flow of 250,000 m$^3$/s, assuming a section of 300 m with sediment volume per channel length of 750 m$^3$/m (full breach in moraine dam) and a section of 200 m with 100 m$^3$/m; (f) probable maximum travel distance of the debris flow of 2500 m (an average slope of 22% and triangular-shaped channel cross section of 10 m depth and 20 m width).

The parameters for the Koltor Lake are: (a) lake volume $V=1.830,000 \text{ m}^3$ (depth measurements in 2005); (b) moraine dam combined with landslides; (c) probable maximum discharge $Q_{\text{max}}=3600 \text{ m}^3/\text{s}$; (d) stable flow path with sediment in the 300-m-long gully at the foot of the lake dam; (e) probable maximum volume of the debris flow 60,000 m$^3$/s (250-m-long section without sediment and 300-m-long section with 200 m$^3$/m); (f) probable maximum travel distance of the debris flow of 300 m (an average slope of 20% and triangular-shaped channel cross section of 20 m depth and 30 m width).

The assessment of the probability based on the above-mentioned parameters is shown in Table 3. The state of moraine dam is the critical factor of the potential outburst in the case of Petrov Lake. The ratio of freeboard to dam height and extreme meteorological events are crucial parameters in the case of Koltor and Lower Adygine lakes. However, the assessment procedure is of a preliminary nature because the precise conditions of potential outburst are unknown.

### Table 3

<table>
<thead>
<tr>
<th>Attribute Qualitative probability</th>
<th>Petrov Lake</th>
<th>Koltor Lake</th>
<th>Lower Adygine Lake</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dam type Moraine (buried ice) Low</td>
<td>High</td>
<td>Medium</td>
<td>Medium to high</td>
</tr>
<tr>
<td>2. Ratio of freeboard to dam height 0.39 Medium</td>
<td>Low</td>
<td>Unlikely</td>
<td>0.3 Low</td>
</tr>
<tr>
<td>3. Ratio of dam width to height 2.32 Low</td>
<td>15.6 Low</td>
<td>Unlikely Low</td>
<td>Low</td>
</tr>
<tr>
<td>4. Impact of waves Frequent Medium</td>
<td>Medium</td>
<td>Unlikely</td>
<td>Low</td>
</tr>
<tr>
<td>5. Extreme meteorologic events Sporadic Medium</td>
<td>High</td>
<td>High</td>
<td>High</td>
</tr>
</tbody>
</table>

Fig. 11. Dam of the Koltor Lake with erosion furrow. (Photo M. Šobr)
Conclusion

Global climate warming causes an intensive melting and retreat of glaciers in mountain areas over the world. This process is evident also in mountain regions of the Northern and Inner Tien-Shan. Melting water of glaciers influences changes in hydrological regime of water streams and causes overfilling of high mountain lakes basins. The dams of many lakes are very unstable and they often burst. The increase of the surface and volume of the Petrov Lake represents potential natural hazard. In case of the lake outburst, flooding of a disposal site of highly toxic waste from the gold mine Kumtor is a real threat. If this happens, the toxic waste containing cyanides could contaminate a large area in the valley of the Naryn River.

Lakes in the Adygine region are situated in front of rapidly retreating valley glacier. If the inflow into the Lower Adygine Lake will increase, approximately 300,000 m³ of water can accumulate in the lake basin. Outburst of such depression would cause a flood in the Al-a-Archa valley and on the territory of Bishkek, the capital of Kyrgyzstan. Because of the accelerating rate of glacier melting and more frequent intensive rains, the probability of the Kolto Lake outburst floods increases. Two overflow events over the dam during the last seven point at the high risk of outburst. When the lake level surface culminates, the volume of collected water is about 2 millions m³. This volume could cause an outburst discharge of several hundreds of m³, which would affect the densely populated Chuykskaya valley.

Acknowledgements

This paper is supported by the research programme of the Czech Ministry of Education “Geographical systems and risk processes in the context of global change and European integration” and by the development project of the Ministry of Environment “Monitoring of high mountain glacier lakes and protection of population against catastrophic impacts of floods caused by rupture of moraine dams”.

References


