Limnologica 40 (2010) 358–364

Contents lists available at ScienceDirect

Limnologica

journal homepage: www.elsevier.de/limno

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

Bohumír Janský *, Miroslav Šobr, Zbyněk Engel

Charles University in Prague, Faculty of Science, Department of Physical Geography and Geoecology, Albertov 6, 128 43 Praha 2, Czech Republic

ARTICLE INFO

Article history:
Received 29 April 2009
Received in revised form
23 November 2009
Accepted 26 November 2009

Keywords:
Genetic classification of lakes
Outburst floods
Hazards assessment
Petrov
Adygine and Koltor lakes
Tien-Shan
Glacial lake
Kyrgyzstan

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.

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 bedrock and lakes dammed by landslides and 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 m^3. 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 Adygine 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 m^3/s. An example of a lake

* Corresponding author.
E-mail address: jansky.b@seznam.cz (B. Janský).

0075-9511/$ - see front matter © 2010 Elsevier GmbH. All rights reserved.
doi:10.1016/j.limno.2009.11.013

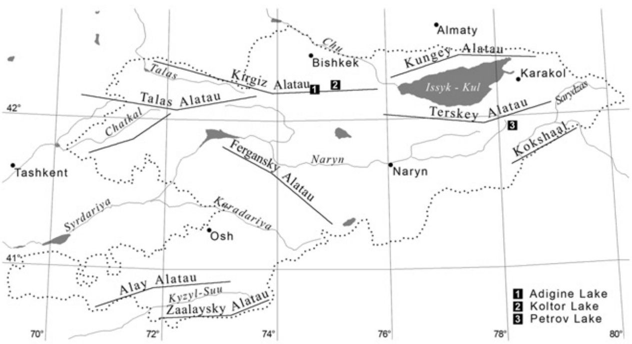

Fig. 1. Localization of study sites.

Fig. 2. Petrov Lake from the moraine dam towards the Petrov glacier. (Photo M. Šobr)

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 (~1:40,000 scale), SPOT panchromatic satellite image (1990 and 1999 with 10 m resolution), a QuickBird panchromatic satellite image (2003, 0.6 m resolution) and GPS mapping (2008). The fluctuations of the Adygine glacier terminus since 1962 are reconstructed 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-Shiirak massive, the Inner Tien-Shan (Fig. 2). The Petrov glacier extends over 69.8 km^2 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
Morphometric characteristics of Petrov, Koltor, Upper and Lower Adygine lakes.

	Petrov Lake	Koltor Lake	Upper Adygine Lake	Lower Adygine Lake
Altitude (m a.s.l.)	3733	2726	3543	3451.5
Area (ha)	390.5	22.15	3.19	0.339
Volume (thous. m^3)	60,309	1830	205.87	6.29
Maximum depth (m)	69.9	14.8	22.2	4.4
Mean depth (m)	15.4	8.3	6.5	1.85
Perimeter (m)	17,030	2387	1023	266
Length (m)	2680	740	364	109
Maximum width (m)	1880	470	151	47

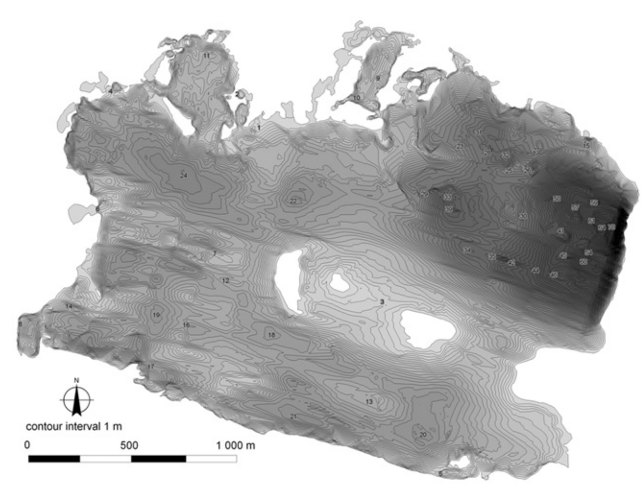

Fig. 3. Bathymetric map of the Petrov Lake based depth measurements from July 2008.

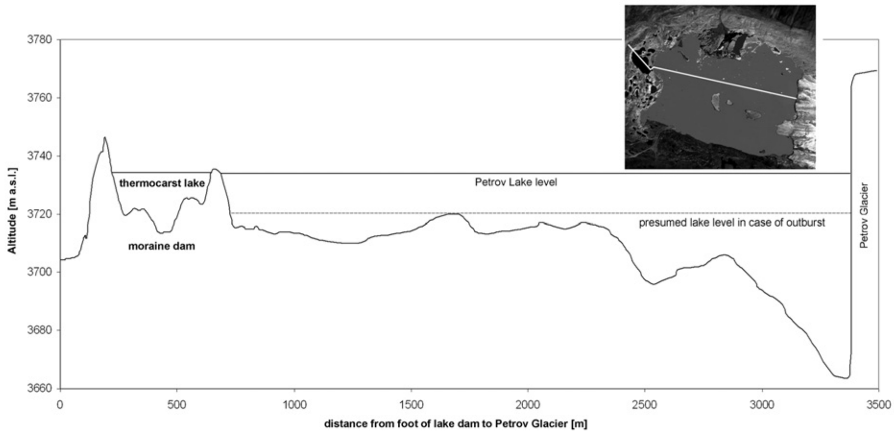

Fig. 4. Longitudinal profile of the Petrov Lake with the depicted surface in case of outburst (12 times exagerated).

Table 2
Increase of the surface area of the Petrov Lake.

Year	Area (km²)	Annual growth (m²)
1911	0.2–0.3	–
1947	0.80	15,000–18,000
1957	0.96	11,000
1980	1.83	37,600
1995	2.78	63,000
2006	3.80	92,700
2009	4.03	77,000

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 km^2, which represents a mean annual increase by 92,700 m^2 (Janský et al., 2009). Since 2006 the lake surface increased to 4.03 km^2 in 2009 (mean annual increase by 77,000 m^2).

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 m^3 in 2008. The maximum depth of the lake is 21.7 m and its average depth is

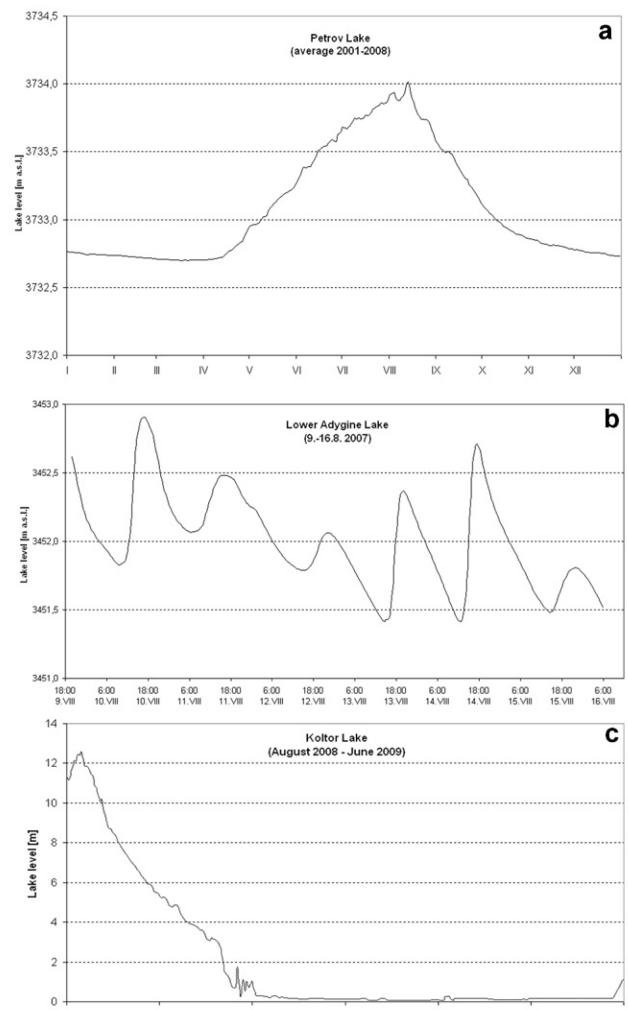

Fig. 5. Seasonal water level oscillations of Petrov (a), Lower Adygine (b) and Koltor (c) lakes.

8.6 m. This lake cuts deeply into the moraine dam representing the most weakened part of the Petrov Lake dam (Fig. 7). The distance between the western shore of this thaw lake and the foot of the moraine dam is only 63 m. The bottom of the lake lies about 9 m above the level of the alluvial plain of the Kumtor River below the dam.

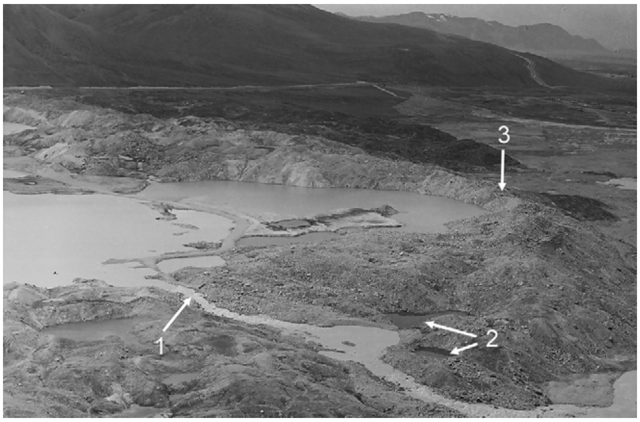

Fig. 6. The largest thermocarst lake in the Petrov Lake dam. 1 – outflow, 2 – thermocarst lakes near the effluent river and 3 – the narrowest part of the moraine dam. (Photo M. šobr)

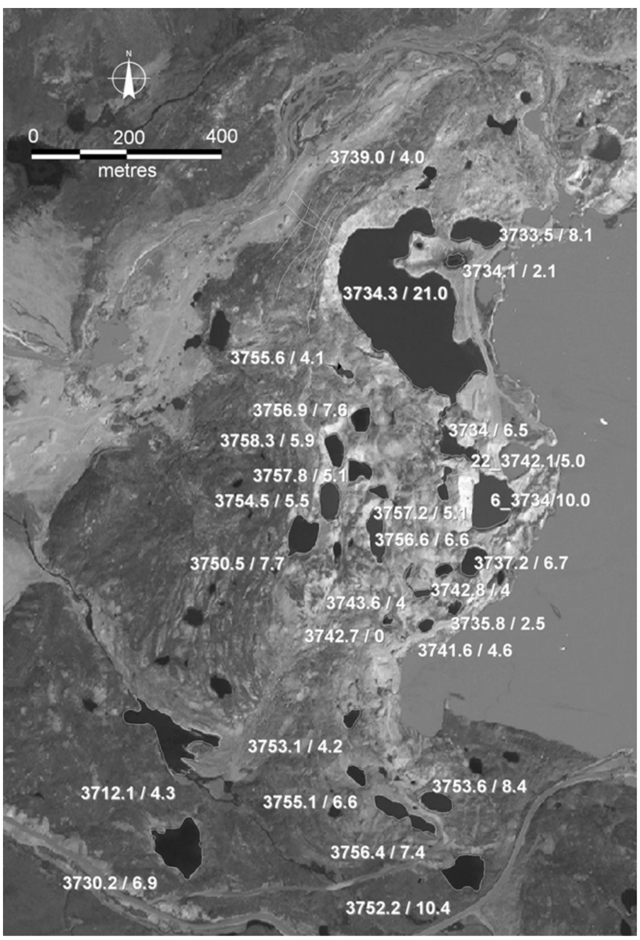

Fig. 7. Thermocarst lakes in the moraine dam of the Petrov Lake with marked lake level altitudes and maximum depths.

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.

Lower Adygine 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

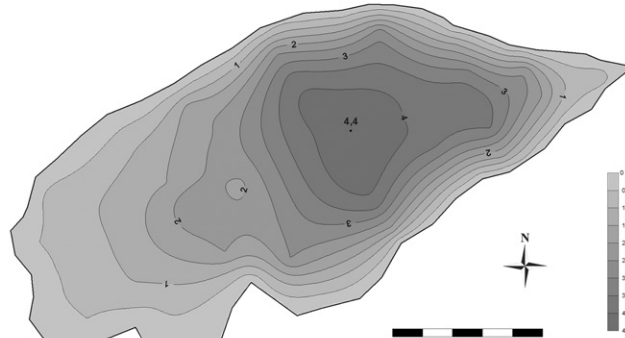

Fig. 8. Bathymetric map of the Lower Adygine Lake.

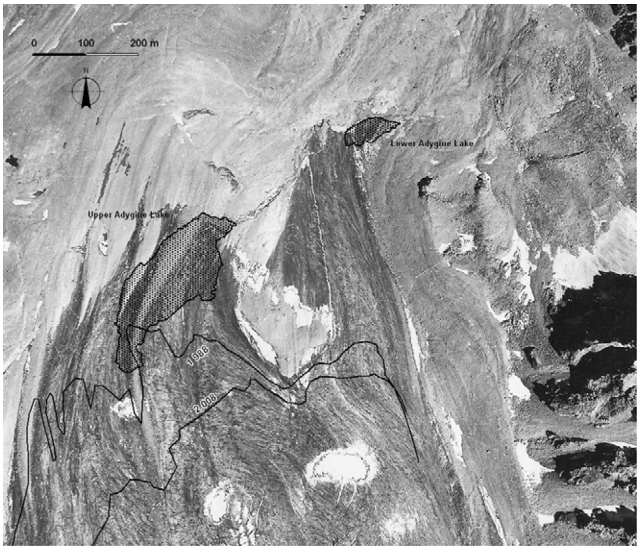

Fig. 9. The development of the Adygine glacier since 1962.

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 m^3 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

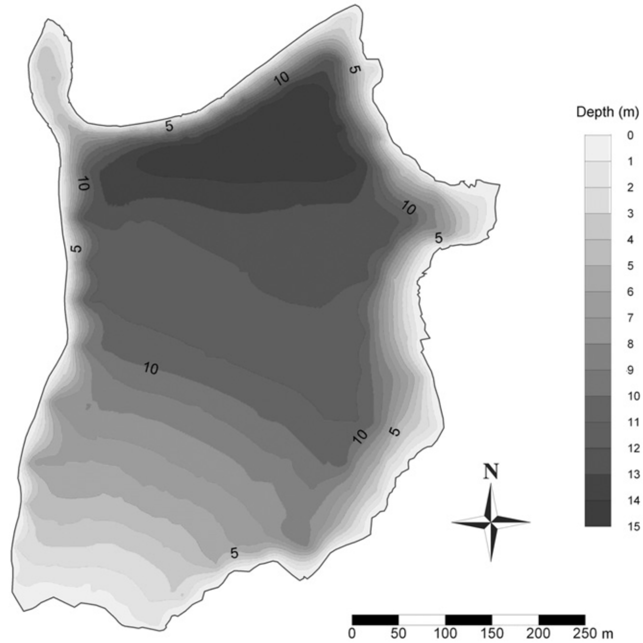

Fig. 10. Bathymetric map of the Koltor Lake.

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. 5c). 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 Tsytsenko, 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 m^3. During the overflow, water flew into the open canal in the dam

Table 3
Indicators for qualitative probability of outburst occurrence.

	Petrov Lake		Koltor Lake		Lower Adygine Lake	
	Attribute	Qualitative probability	Attribute	Qualitative probability	Attribute	Qualitative probability
1. Dam type	Moraine (buried ice)	High	Moraine and landslides	Medium to high	Moraine (buried ice)	High
2. Ratio of freeboard to dam height	0.39	Medium	0.05	High	0.3	Low
3. Ratio of dam width to height	2.32	Low	15.6	Low	6.2	Low
4. Impact of waves	Frequent	Medium	Unlikely	Low	Unlikely	Low
5. Extreme meteorologic events	Sporadic	Medium	Frequent	High	Frequent	High

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

crest high above the erosion furrow. Among processes which trigger lake outbursts debris-flows are of major interest. They occur repeatedly, mostly in fixed trajectories. The Koltor Lake is immediately menaced by debris-flows from three slopes furrows in the eastern valley slope. The trajectories of these furrows are characterized by a high exaggeration (up to 400 m) and inclination (20–30°). In addition, a high quantity of weathered material is present in the source area of furrows (Fig. 11).

A subsurface type of flood can be expected, with a large outflow, which could reach several hundred m^3. The danger of a flood event is increasing due to more intense melting of the glaciers and the increased frequency of torrential rain. These factors are causing the water level to rise, leading to the emergence of a surface outlet, erosive activities which are weakening the lake's dam. At present there is no immediate danger of an outburst, but the situation could change if erosive trenches emerge or if overflow over the lake's dam occur. The valley is relatively wide, until the site of the subterranean outlet; however, the average slope over a distance of 1.9 km reaches 20.4%. After this point the valley is very narrow and steep until the confluence with the Kegety River (5.5 km, 14.3%). As the river continues, the valley widens and the surrounding area is used for agriculture. The nearest settlement is the village of Kegety, roughly 17.5 km away from the lake. The valley of the Koltor and Kegety Rivers is very sparsely populated. Only a few solitary dwellings of forest labourers, yurts of shepherd families and the location of a children's summer camp, which is undergoing reconstruction, are located in this area. At the sub-alpine level, however, there is a significantly higher density of settlement with a number of smaller villages, which in the event of the lake 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=60.309 millions m^3 (depth measurements in 2008); (b) moraine dam with 50–70% of buried ice ;(c) probable maximum discharge Q_{max}=74,783 m^3/s (Q_{max}=2 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/s (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 m^3 (depth measurements in 2006); (b) moraine dam with buried ice; (c) probable maximum discharge Q_{max}=12.58 m^3/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 m^3 (depth measurements in 2005); (b) moraine dam combined with landslides; (c) probable maximum discharge Q_{max}=3600 m^3/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.

Conclusion

Global climate warming causes an intensive melting and retreat of glaciers in mountains 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 m^3 of water can accumulate in the lake basin. Outburst of such depression would cause a flood in the Ala-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 Koltor 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 m^3. This volume could cause an outburst discharge of several hundreds of m^3, which would affect the densely populated Chuyskaya 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

Carey, M., 2008. Disasters, development, and Glacial Lake control in twentieth-century, Peru. In: Wiegandt, E. (Ed.), Mountains: Sources of Water, Sources of Knowledge. Advances in Global Change Research, vol. 31. Springer, pp. 181–196.

Clague, J.J., Evans, S.G., 1994. Formation and failure of natural dams in the Canadian Cordillera. Geol. Surv. Canada, Bull. 464, 1–35.

Clague, J.J., Evans, S.G., 2000. A review of catastrophic drainage of moraine dammed lakes in British Columbia. Q. Sci. Rev. 19, 1763–1783.

Davydov, L.K., 1927. Lednik Petrova (Petrov Glacier). Hydrometeorological Institute, Taskhent.

Dyurgerov, M., 1995. Olednenie Ťan-Šana (Tien-Shan Glaciations). Viniti, Moskva.

Grigoriev, A.A., Frolov, A.I., 1966. Otchet po rekognoscirovochnomu obsledovaniju vysokogornych ozer Kirgizii. (Report on Observations of Mountain Lakes of Kyrgyzstan). Kyrgyz Hydrometeorlogical Institute, Frunze.

Haeberli, W., 1983. Frequency and characteristics of glacier floods in the Swiss Alps. Ann. Glaciol. 4, 85–90.

Haeberli, W., Alean, J.-C., Müller, P., Funk, M., 1989. Assessing the risks from glacier hazards in high mountain regions: some experiences in the Swiss Alps. Ann. Glaciol. 13, 77–101.

Hewitt, K.J., 1982. Natural Dams and Outburst Floods in the Karakoram Himalaya, vol. 138. IAHS Publication, Wallingford 259–269.

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, 316–330.

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

Janský, B., Šobr, M., Yerokhin, S.A., 2006. Typology of high mountain lakes of Kyrgyzstan with regard to the risk of their rupture. Limnol. Rev. 6, 135–140.

Janský, B., Engel, Z., Šobr, M., Yerokhin, S.A., Beneš, V., Špaček, K., 2009. The evolution of Petrov Lake and Moraine Dam rupture risk (Tien-Shan, Kyrgyzstan)Natural Hazards 50 (1), 83–96.

Karpov, V.G., Tsytsenko, K.V., 1966. Otchet po rekognoscirovochnomu obsledovaniju vysokogornych ozer Kirgiziji (Report on Observations of Mountain Lakes of Kyrgyzstan). State Institute of Geology, Bishkek.

Kattelmann, R., 2003. Glacial lake outburst floods in the Nepal Himalaya: a manageable hazard? Natural Hazards 28, 145–154.

Kaulbars, A.V., 1875. Materialy po geografii Tian Shana, sobranyje vo vremja puteshestvija 1869 (Materials on Geography of the Tien-Shan, Collected within Expedition in 1869). Russian Geographical Society, Sankt Peterburg.

Mayer, C., Lambrecht, A., Hagg, W., Helm, A., Scharrer, K., 2008. Post-drainage ice dam response at Lake Merzbacher, Inylchek Glacier, Kyrgyzstan. Geografiska Ann. Ser. A 90 (1), 87–96.

McKillop, R., Clague, J., 2003. Statistical, remote sensing-based approach for estimating the probability of catastrophic drainage from moraine-dammed lakes in southwestern British Columbia. Glob. Planet. Change 56 (1–2), 153–171.

Meiners, S., 1997. Historical to Post Glacial glaciation and their differentiation from the Late Glacial period on examples of the Tien-Shan and the N.W. Karakorum. GeoJournal 42 (2–3), 259–302.

Richardson, S.D., Reynolds, J.M., 2000. An overview of glacial hazards in the Himalayas. Q. Int. 65/66, 31–47.

Shnitnikov, A.V., 1975. Iz istorii ozer vnutrenego Tjan-Šana (History of lakes of interior Tjan-Shan), Ozera Kazachstana i Kirgiziji i jich istorija (Lakes of Kazachstan and Kyrgyzstan and their History). Nauka, Sankt Peterburg, pp. 229–238.

Sevastianov, D.V., Funtikov, A.B., 1981. Novye dannye ob evolucii vysokogornogo ozera u konca lednika Petrova (New data on the evolution of the mountainous lake in front of the Petrov glacier). Izvestia VGO 113 (5), 430–435.

Walder, J.S., Driedger, C.L., 1995. Frequent outburst floods from South Tahoma Glacier, Mount Rainier, U.S.A.: relation to debris flows, meteorological origin and implications for subglacial hydrology. J. Glaciol. 41, 1–10.

Yerokhin, S.A., Aleshin, A.K., 1997. Raboty po obsledovaniyu za sostoyaniem plotiny ozera Koltor na period pereliva vody cherez yego greben i izucheniye sostava i stroeniya plotiny (Monitoring of Structure of the Dam of Koltor Lake in Time of Overflow). State Institute of Geology, Bishkek.

Yerokhin, S.A., 2002. Tipy gornykh ozer a kratkaya ikh kharakteristika (Typology of High-mountain Lakes and their Characteristic). State Institute of Geology, Bishkek.

Yerokhin, S.A., 2003. Izucheniye i obsledovaniye bezopasnosti ot proryva vysokogornykh ozer na teritorii Kyrgyzskoy Respubliki (Study and Monitoring of Dam Failure Safety of High-mountains Lakes in Kyrgyz Republic). State Institute of Geology, Bishkek.