Chapter 7: High-altitude lake outburst: Tien Shan case study

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1. Introduction

Monitoring of mountain lakes in the territory of Kyrgyzia realized during the 1990s by the Kyrgyz Agency for Geology revealed 15 lakes at the stage of imminent risk of rupture (Yerokhin, 2002). According to their development, these lakes may be classified as tectonic, glacier, morainic-glacier, morainic, lakes dammed by a rock step and slide lakes (Janský *et al.*, 2006). The majority of the endangered Kyrgyz lakes belongs to one of the last three mentioned genetic types.

Morainic-glacier lakes develop in basins in intramorainic depressions after retreat of glaciers. The bottom and the banks (walls) of the lake are formed by impermeable materials, mainly by pure and morainic ice and frozen debris material. On this impermeable underlayer water is cumulated and in summer it warms up to 8–10 °C, which causes a quick melting of ice and of frozen clastic material in the underlayer. The lake basin is getting progressively deeper and its volume is increasing to reach dozens to millions of m^3. The greatest lake of this type in the territory of Kyrgyzstan is the Petrov Lake in the Ak-Shiyrak massif in the southern Tien Shan, the area of which has been increasing during the last 10 years in average by 9 ha each year to reach the area of about 380 ha.

Lakes dammed by a rock step (riegel) arise in glacier valleys behind a low barrier or a step from resistant rocks (Benn *et al.* 1998, Hutchinson 1957). This belt of rocks resistant to glacier erosional activities forms across the valley a step behind which melting glacier water accumulates after the retreat of the glacier. Water flows out the lake in the lowest point of this step. As the lake dam is formed by a resistant rock step, these lakes are not much dangerous. The risk in these lakes exists only in places where this step is covered by moraine material. Outflow from these lakes is mostly underground through the moraine, mostly on the level of the rock step. Underground canals can nevertheless get filled up which can cause an interruption or reduction of the underground outflow and a subsequent rising of the level of the lake. Because of the height of moraines (even more than 20 m), this process is particularly dangerous. If a rupture of such a lake occurs, water mostly overflows to the level of the lowest point of the rock step. Such bursting occurred for instance in 1997 in the At-Jailoo Lake in the Kegety River basin in the northern slope of the Kyrgyz Ridge.

Lakes dammed by a landslide or rockfall accumulation are characterized by a great volume of retained water, so that bursting of these lakes is very dangerous. Outflow is mostly underground, but it can also be on surface (for instance by the maximal filling up), or both types may be combined. The passage from one form of outflow to another can be very dangerous. Flows during bursting may reach hundreds or even thousands of m^3/s. An example of a lake the dam of which was formed by a slide and rockfall is the Koltor Lake on the northern slope of the Kyrgyz Ridge. Also the very voluminous Sarychelek Lake (515 million m^3) on the southern slope of Chatkal Ridge is of this type.

Adygine, Koltor and Petrov lakes were selected and studied in the Tien Shan Mountains as a case study 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.

2. Petrov Lake

Petrov Lake (Figure 1) is located in the foreground of the identically called glacier, which is situated on the northwestern slope of Ak-Sijrak massive in southern Tien Shan and is the largest glacier in the whole River Naryn catchment. This hollow glacier is 69.8 km^2 wide and 23 km long. The maximal absolute altitude of the lake surface is 3,734 m.

The first information on Petrov Lake and glacier is given by Kaulbars (1875). The subsequent development of the lake was described according to reports by Davidov (1927), Bondarev (1963), Sevastyanov and Funtikov (1981). According to a map from 1911, the surface of the lake was 0.2 or 0.3 km^2. Up to 1947, the lake extended to approximately 0.85 km^2 which represents a yearly increase of the surface by 0.015 or 0.018 km^2. In the next aerial photograph from 1957, Petrov Lake takes up as much as 0.96 km^2 whereas the dynamics of the surface enlargement in 1947–1957 decreased to 0.011 km^2 a year (Bondarev, 1963). This is apparently related to the growth of Petrov glacier in 1943–1957. From 1957 to 1977, the surface of the lake expanded 1.9 times, which means a yearly increase of the lake surface area by 0.043 km^2. In 1978–1995, the lake grew by about 0.053 km^2 every year and it reached the size of 2.78 km^2. The highest dynamism of the lake water surface increase was nevertheless ascertained only recently (1995–2006). During the eleven years since the last measurement the lake has reached its present area of 3.80 km^2, which represents a mean annual increase by 92,700 m^2 (Janský *et al.*, in print).

Petrov Lake is formed by two partial basins separated by a belt of shallows and islands which are a part of the central moraine formed on the contact of the two main tongues of the Petrov glacier. The southern basin has a smaller area and is sensibly shallower with a maximal depth of 21 m in the middle part of the depression (Figure 2). Above the front of the glacier, there is a large shallow-water area formed by glacial and fluvioglacial sediments which have been transported there by the glacier and recently also by a relatively strong surface flow. It is not excluded that beneath

Figure 1 View from the moraine dam of the Petrov Lake towards the Petrov glacier (Photo M. Šobr)

these sediments there is buried ice, the melting of which would result into a further increase of the lake volume.

The northern basin of the lake has a very complicated structure. In the direction from the lake dam, there are four consecutive relatively pronounced partial depressions. These forms document the speed of the retreat of both glacier tongues. The first basin is up to 23 m deep, the second one is 22 m deep. The first two partial basins have practically the same depth in the northern and in the southern part of the lake, while the partial basins in the northern part of the lake have a larger area. The greatest difference is in the third partial basin – in the southern part of the lake its depth is much lower (20 m) against the 38 m in the northern part of the lake. The last (fourth) basin, which is not developed in the southern part, is the deepest one in the southern part (probably more than 70 m – see Figure 3) and it ends at the front of the glacier. It is deepened into the rock underlayer which is proved by rock outcrops in the peninsula at the front of the glacier.

In the case of a dam rupture in the area of the Blue Gulf and of a subsequent water outflow from the northern part of the lake, also water from the southern part of the basin would flow away up to the level of the step between the both basins in a depth of 13 m below the present water surface. In the case of an outburst of the lake and flowing off of a 13 m layer of water, in total about 37 million m^3 of water would flow away from the lake, which is 62 % of the total lake volume. In the northern part of the

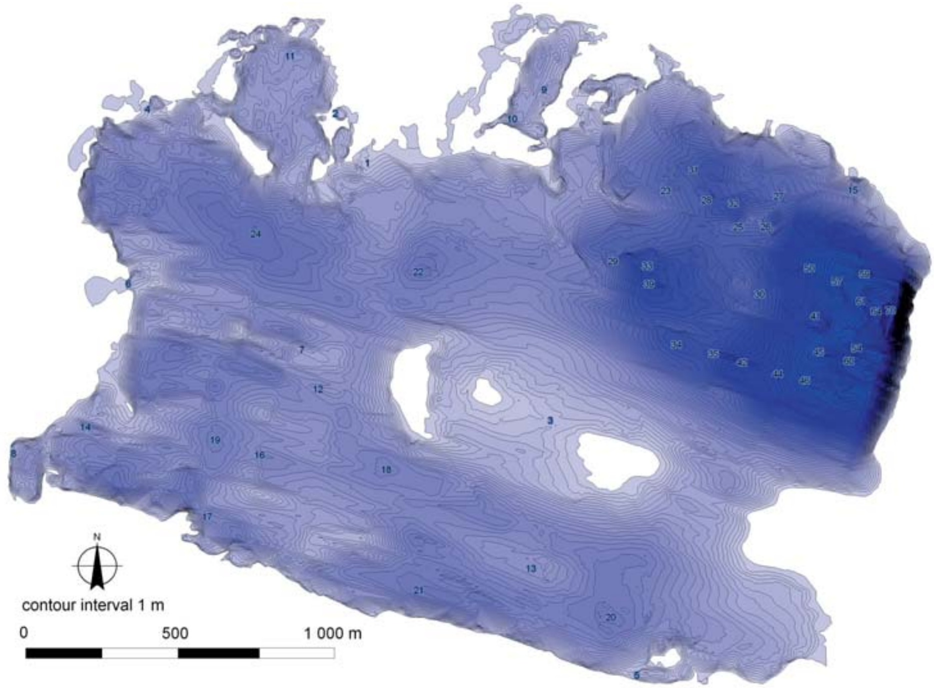

Figure 2 Bathymetric map of the Petrov Lake originated by bathymetric measurements in July 2006. It was used 6,200 points measurements of depth to model lake basin.

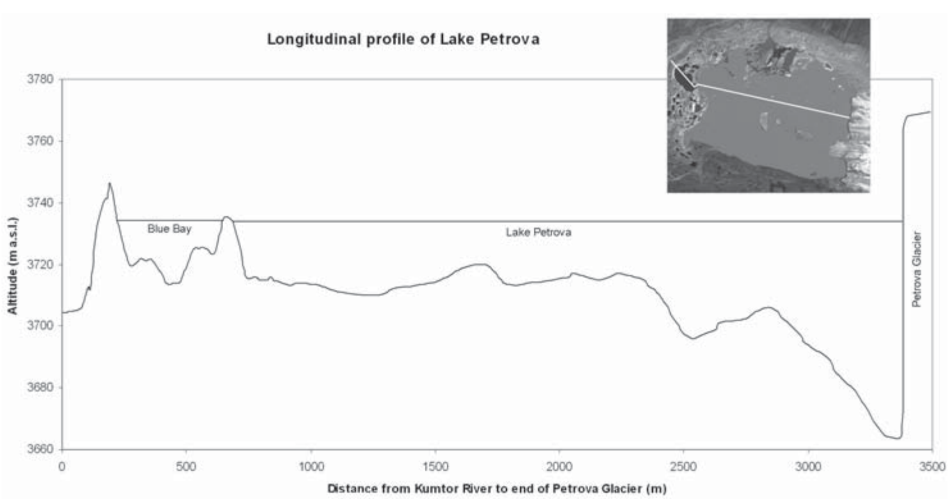

Figure 3 Longitudial profile of Lake Petrova created on the basis of cartometric measurements on bathymetric map

lake, the individual steps are situated even deeper between the partial basins. The first and the second basin are separated by a step in a depth of 17 m, the same situation is between the second and the third partial basin. The third and the fourth basin are separated by a step in a depth of 28 m. If a rupture of the lake would occur in a depth of 17 m, the northeastern part of the lake would largely contribute to the quantity of out flown water.

The oscillation of the Petrov Lake surface during the year corresponds to the annual curve of air temperature. A similar tendency is manifested also by outflows of the Kumtor River at its flowing off the Petrov Lake. The lake surface begins to increase at the end of April when maximal day temperatures are above the freezing point, the maximal increase of the lake surface occurs in May when also mean daily temperatures are above the freezing point and snow and ice melting gets intensive. Slight oscillations of the lake surface correspond to oscillations of mean daily temperatures. The increase of the lake surface level continues till the end of July, when the quantity of water in the lakes culminates. Then follows a progressive decrease of the lake surface down to its minimal level at the beginning of December (3,734.78 m a.s.l.), which remains nearly to the end of April.

The most important processes which endanger the existence of the lake are in the area of accumulative glacier relief and are directly related to the mass balance of the

Figure 4 The greatest lake of intramorainic depressions in the territory of Kyrgyzstan is the Petrov Lake. 1 – surface outflow throughout the moraine material, 2 – in moraine is located 29 important (significant) thermocarstic lakes, there are two relatively small examples, 3 – narrowest part of the moraine dam (Photo M. Šobr).

Figure 5 Thermocarstic lakes in moraine which dammed the Petrov Lake

Petrov glacier. The Petrov Lake is closed by a terminal moraine and lateral moraines at the foot of the valley slopes (Figure 4). These form the shoreline all the way to the current terminal moraine. While the lateral moraines are of no serious danger to the lake, the eastern and the western banks are under a continual development. The glacier dam on the western side of the lake is affected by the most destructive processes. It is exposed to oscillation of lake water and to degradation processes in the moraine area.

The deciding factor for the moraine dam development is the presence of buried ice which is the cause of the instability and the transient lifetime of the current dam. Ice, which is forming the major part of the overall moraine mass, protrudes in many places of the sedimentary cover and represents the most dynamic part of the dam. Degradation of the dead ice is accompanied by relief sinking, by emerging of thermokarstic lakes, sliding of morainic sediment and down-slope falling (Figure 5). Major changes to the sedimentary cover of the dam are caused by intensive periglacial processes. Many active periglacial landforms are developed in the dam. 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 thermokarstic lakes. Narrow strips of dry land between individual lakes are constantly sinking which has caused hydrological connecting of the lakes. An especially intensive development can be observed within the large lake in the north-east part of the dam called the “Blue Gulf”. In comparison with the last mapping from 1995, its surface has increased to 0.087 km^2, it contains 745.569 m^3 of water, its maximum depth is 21.1 m and its average depth is 5.14 m. This gulf cuts deeply into the body of the dam and dissects it. The fact that this is the place where the dam is the most weakened is worth of attention. The direct distance between the gulf shore and the outer slope of the dam on the windward part of the dam is only 63 m at the water level. On the profile across the dam, the bottom of Blue Gulf is distinct as it lies about 9 m above the level of the alluvial plain of the Kumtor River below the dam. The depression with the lowest dam level being situated at only 11.9 m above the lake level is also noteworthy.

The Petrov Lake develops rapidly in relation to the accelerating retreat of the Petrov glacier. Recently its area has been increasing by more than 92 thousand square meters per year. The increase of the lake size and volume along with a weakening of the moraine stability causes an extremely dangerous situation which could result into a large-scale natural catastrophe.

3. Adygine Lake

The Adygine lake area is situated in the upper part of the valley closure on the northern side of the Kyrgyz ridge. The Adygine River belongs to the Ala-Archa catchment, it flows into it from the left side after some 6 km. It springs from a glacier from which many creeks are flowing – they flow together above the glacier front and locally form

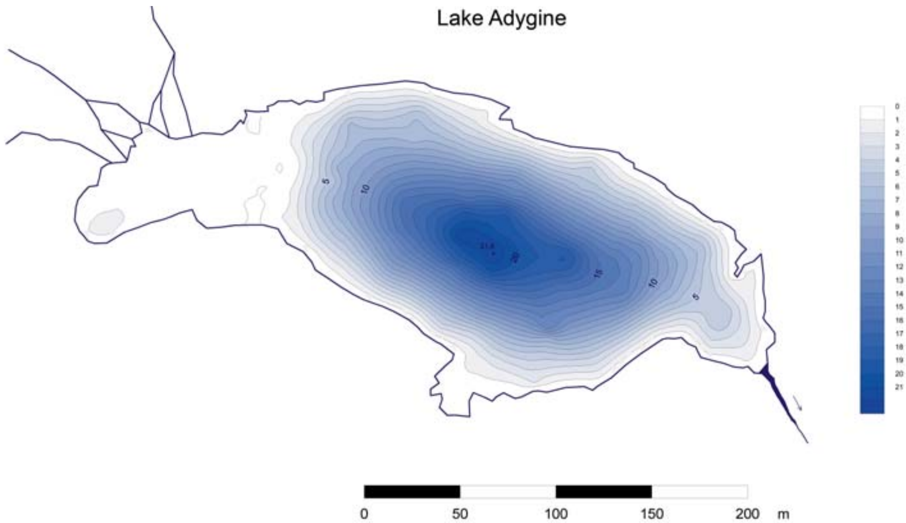

Figure 6 Bathymetric map of the Adygine Lake

Figure 7 Meteorological station situated near Lake Upper Adygine (Photo M. Šobr)

new shallow proglacial lakes. The water from these lakes flows either into the Upper Adygine Lake or directly into an elongated depression between the eastern valley slope and the moraine.

The Upper Adygine Lake (Figure 6) was formed in a large depression within the active moraine. Its dam is formed by a resistant rock step, in the point of outflow strongly weathered and dissected into larger rock blocks. The maximal depth of 21.6 m was found in the central part of the lake basin. The lake area is 3.27 ha, the lake basin volume 208,000 m^3. The outflow from the lake is both surface and underground. In the summer period water flows in an about 3 m width over a weathered rock step, in winter it flows away only through underground canals, the course is not known. Summer flows of the surface outflow from the lake oscillate between 0.5 and 0.7 m^3/s.

The outflow from the Upper Adygine Lake fills the Lower Adygine Lake which was formed in an about 50 m deep and 150 m long thermokarstic depression which is probably supplied, beside the surface water, also by an underground canal. The volume of the Lower Lake largely oscillates during the day – approximately between 10,000 and 15,000 m^3. The maximal depth of the lake in the afternoon hours is 4.7 m. A high oscillation of the water level and consequently of the lake volume during the day is connected with the limited capacity of the underground canals draining the Lower Lake. If water flow into the Lower Lake increases or if the Upper Lake bursts open, approximately 300,000 m^3 of water can accumulate in the lower basin. A rupture of such depression would mean a large-scale catastrophe for the main Ala-Archa valley and also the capital city of Bishkek would be endangered.

Beside the two above-mentioned lakes, other four smaller lakes are being formed above the retreating Adygine glacier. Although they are not likely to burst open now, they can further develop. Also these small lakes can be dangerous in future, as it was the case of a small lake (of about 100,000 m^3) which was situated above the western tongue of the Adygine glacier up to July 2005, when it burst open. This rupture is proved by denuded underground canals reaching down to deep underground siphons.

The main source of water for these lakes is the Adygine glacier filling up the large valley closure in the northern slope of the Sokuluk ridge. In spite of a favourable northward orientation, only a short glacier tongue falls from the accumulation area with its front at 3,605 m. The development of the glacier since 1962 witnesses about

Figure 8 Measurements of water discharge in outflow from valley Adygine (Photo J. Česák)

a slow retreat of the glacier front which has been accelerating these last years. While in 1962 the tongue ended at an altitude of 3,580 m near the present outlet from the Adygine 2 Lake and in 1988 some 200 m away at the opposite end of the lake at the inlet, during the following 18 years it retreated some 250 m to the altitude of 3,605 m. In the case of a further retreat of the glacier, we can expect an intensive development of the lakes in its foreland (including the possible rupture of the western lakes) and formation of new lakes. The retreat of the glacier, the development and hydrological regime of the lakes in this locality will be therefore monitored also in the future. For the purpose of monitoring the hydrological balance of the glacier, a meteorological station (see Figure 7) was established in its proximity. In the Ala-Archa valley an automatic level gauge for continuous registration of water level oscillation was installed; in future, it will be a part of the early warning system for the capital city of Bishkek (Figure 8).

4. Koltor Lake

The lake is situated in the by glacier remodelled part of the valley of the Koltor River which drains the northern slope of the central Kyrgyz ridge. The river rising in Anastasie glacier front has a right-side affluent from Langvaren glacier, the tongues of which are situated at an altitude of more than 3,500 m. After about 2 km the river enters a complicated labyrinth of a huge glacier-morainic complex covered on the surface and on its sides by rough debris and rock blocs. This rock glacier contains a great quantity of buried ice and a complicated system of hollows and cross canals and largely influences the glacier outflow regime of the Koltor River. This river flows at an altitude of 2,853 m from the frontal moraine of the glacier and flows through a closed valley into a 1,700 m distant lake.

The Koltor Lake (Figure 9) was probably formed in the Daun period as a morainic lake and its basin was probably at first shallow (Yerokhin, 2003). During the following period the moraine was covered by a huge rockfall from the right side of the valley and later by a smaller rockfall from the left side of the valley. The so consolidated dam across the valley was about 250 m wide and more than 300 m long. In the formed basin a lake started to fill; its development was influenced both by the stability and permeability of the dam and by long-term and seasonal oscillations of the inflow. The inflow was the main factor of siltation of the lake basin.

At present, the lake basin has a regular shape corresponding to the valley-type of the lake dammed by morainic material of rockslides from both lateral slopes. Its greatest depth (14.8 in maximum) is found 30 to 50 m above the dam and it is progressively decreasing in the direction to the lake inflow. The area, the volume and further hydrographical characteristics of the lake depend on the water surface level. With its surface at an altitude of 2,726 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 (see bathymetric map on Figure 10).

The lake is supplied by water from glaciers, from seasonal snow cover, rainfall and underground water headsprings. The dominant part of melting glaciers manifests

Figure 9 The Lake Koltor is dammed by older landslide (1) and younger landslide (2), that are over moraine which is from daun age (Photo S. Yerokhin)

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 Shitnikov (1975), it rises to the end of April by 3 to 4 m. When the snow has melted, the rising of the water level gets slower and increases again from the middle of June when glaciers in the spring area of the Koltor River begin to 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

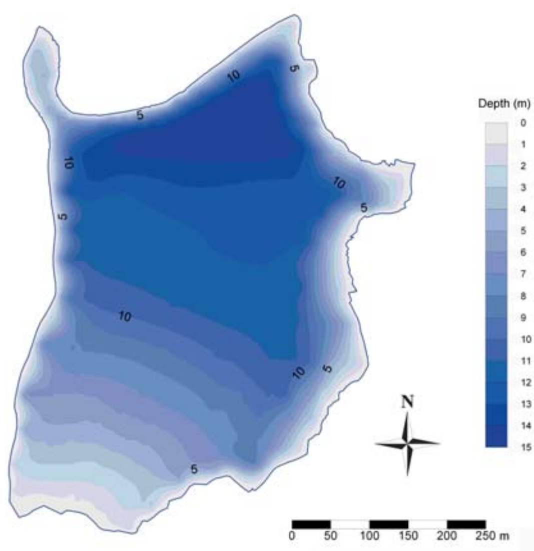

Figure 10 Bathymetric map of the Koltor Lake

maximal level. The lake is covered by ice mostly to the end of March and then the hydrological cycle recurs. The daily hydrological regime of the lake is influenced above all by melting of glaciers and it manifests by water level oscillation. 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 main outflow – underground – is situated in the gulf in the north-western part of the lake. There are probably more drainage canals; the small ones get probably opened and closed in the course of the year. Geophysical methods enabled to ascertain the ways of leaking occurring along the both sides of the erosion furrow. These leakages may cause a further sinking of the outer part of the dam and its reduction. 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 in1966, when, according to local witnesses, a 160 m long, 12 to 28 m wide and 1 to 4 m deep erosion furrow was formed at the low side of the dam (Karpov, Tsytsenko 1966). The dam was then overflowed in July and August 1997 (Yerokhin, Aleshin 1997) and on the 23rd and 24th of July 2004. At this occasion, the dam was sensibly overflowed (up to the height of about 30 cm above the lowest overflow point) and the erosion furrow on its outer side was deepened (Figures 11 and 12). A huge stone stream fell into the lake basin and caused an overspill of the same water volume over the dam. The last overflow occurred after an intensive snow melting in July 2006.

Figure 11 Aerial part of dame of the Lake Koltor with big gully (Photo M. Šobr)

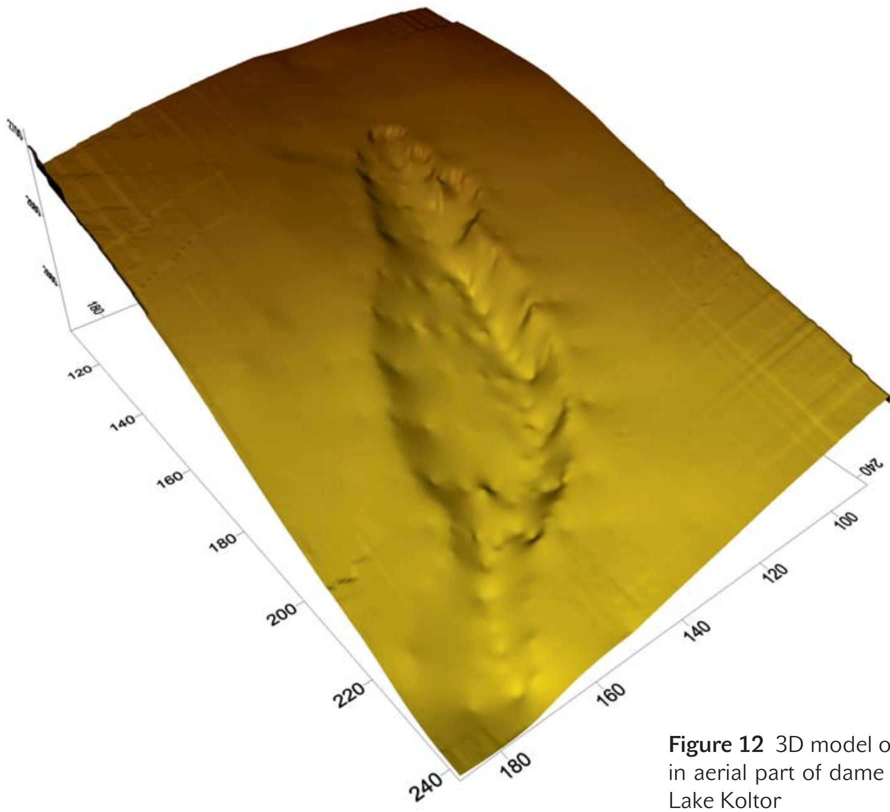

Figure 12 3D model of gully in aerial part of dame of the Lake Koltor

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 crest high above the erosion furrow.

Among risk geomorphologic processes, the highest dynamism is at present found in stone streams. They occur repeatedly, mostly in fixed trajectories. The Koltor Lake is immediately menaced by stone streams from three slope furrows in the eastern valley slope, the trajectories of which reach to the area of dejection cones on the eastern bank of the lake. Because of the profile of their trajectories characterized by a high exaggeration (up to 400 m) and by a high mean inclination (20–30°), the local stone streams manifest high speed and transport energy and, under favourable climatic conditions, their transport down to the present lake cannot be excluded. In addition, a high quantity of weathered material in the source area of stone streams guarantees that their activities will also in the future be limited only by exogenous factors. Another risk factor consists in depressions in the area of the rock glacier which are periodically filled by water. This water flows away by underground canals. In the case of their blockage and formation of a lake, the retained water can suddenly escape and the water level of the Koltor Lake can rapidly rise.

5. Conclusion

Global climate warming causes an intensive melting and retreat of glaciers in the majority of high mountains all over the world. This process is evident also in mountain regions of central Tien Shan. 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 open.

The increase of the surface and volume of the Petrov Lake accompanied by the decrease of stability of the dam represents an extremely dangerous situation that can end in a natural disaster. In case of the lake dam rupture, 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 would contaminate a large area in the valley of the Naryn River, including two large dam reservoirs, and would reach as far as to the neighbouring Uzbekistan. Even if the flooding of the disposal site does not occur, the damage after the lake dam rupture will be immense. The impact of the flood would be further intensified by high summer flow rates and by filling of the dam reservoirs with melting water from the glaciers.

Lakes in the Adygine region are a very dynamic geomorphologic system. If the inflow of water into the Lower Lake is in the future further increasing or if the Upper Lake gets burst open, approximately 300,000 m^3 of water can accumulate in the lower basin. Rupture of such depression would mean a flood catastrophe of huge dimensions for the main river valley of Ala-Archa and also the capital city of Kyrghyzstan, Bishkek, will be endangered.

Because of the increasing intensity of glacier melting and more frequent torrential rains, the Koltor Lake is considered as very dangerous. Two floodings over of the dam during the seven last years witness about an increasing risk of the lake dam rupture. When the water level in the lake is at its maximum, the volume of the retained water is about 2 millions m^3. This volume would, after a catastrophic rupture, cause a flood wave of several hundreds of m^3, which would affect the densely populated Chujskaja valley.

Acknowledgement

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