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Department of Chemical and Nuclear Engineering.

MASTER THESIS

RISK ASSESSMENT OF PETROV'S GLACIAL LAKE OUTBURST FLOODS (KYRGYZSTAN).

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To my parents

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ABSTRACT

Recent trends in climate change in combination with strong pressing on the weak stable high mountain natural environment may lead to a degradation of permafrost sites, glacier deviation, development of destructive processes in soils, and instability of natural and man-caused objects, including ecologically hazardous ones, to which it is necessary to add the mining waste storage tailings. Nowadays we do possess sufficient knowledge and there is a few data allowing to safety prediction of long term interaction of hydraulic facilities with natural high-level geologic environment. But, the permanent climate changing complicates the analysis of future events.

This thesis shows an Environmental Risk Analysis (ERA) for systematic and comprehensive study of the status of Petrov’s glacial lake also it's possible assessment of the hazard it pose and of the vulnerability of downstream people and property. The main purpose of the study is the impact of outburst wave of the lake on a nearly tailings pond of "Kumtor" mining company. The possibility of this scenario would lead to an ecological catastrophe not only in Kyrgyzstan but also throughout Central Asia.

Several possible factors have been selected for ERA in the development of events. In the study took into account the annual water increasing in the lake, seismic activity and structure (moraine dam) of the study area, the possible events in the tailings after the flood.

Further practice of object using, detailed monitoring of dam state, engineering-geological and geophysical surveying on the laying area revealed a whole series of factors (conditions and processes), which may lead to an object failure with disastrous environmental effects. Symbolically there are three groups of risk factors:

- internal physico-geological factors in dam foundation and in Petrov’s moraine dam body triggering its instability;
- hydrogeological and hydrological factors within a catchment area;
- glaciologic and thermodynamic processes.

This analysis was conducted using the International Standard ISO 14031 Environmental performance evaluation and Environmental Risk Assessment, March 1999. To get to quantify the risks of each these cases, it is necessary to identify and familiarize themselves with the most commonly reported accidents and identified from the historical sources that initiated these accidents (initiators). With these accidents recreated in an event tree; by which assesses the potential consequences associated with failure on a simulating of alteration in the process, the event trees used a prospective analysis (from an initiating event is determine their possible consequences).

RESUMEN DE LA TESIS

Las últimas tendencias en el cambio climático, en combinación con una fuerte presión sobre el debil entorno natural estable de alta montaña pueden dar lugar a una degradación del permafrost, desviacion glaciar, el desarrollo de los procesos destructivos en los suelos y la inestabilidad de origen natural y humano – objetos causados, incluyendo ecologicamente peligrosos, a los que hay que añadir los relaves mineros de almacenamiento de residuos.

Esta tesis muestra un Análisis de Riesgos Ambientales para el estudio sistemático y exhaustivo de la situación del lago glacial de Petrov también es posible la evaluación de la amenaza que plantean y de la vulnerabilidad de las personas y de los bienes intermedios. Pero el objetivo principal del estudio es el impacto de la onda de explosión del lago en una balsa de residuos cerca de la minera "Kumtor". La posibilidad de este escenario llevaría a una catástrofe ecológica no sólo en Kirguistán sino también en toda Asia Central.

Para el análisis de riesgos se ha seleccionado varios factores posibles en el desarrollo de los acontecimientos. En el estudio se tuvo en cuenta el agua anual cada vez mayor en el lago, la actividad y la estructura sísmica (presa morrena) del área de estudio, los posibles eventos en los relaves después del diluvio.

Además la práctica de los objetos que utilizan, un seguimiento detallado del estado de la presa, la ingeniería - geológica y estudios geofísicos en la zona por la que se puso de manifiesto toda una serie de factores (las condiciones y procesos), lo que puede conducir a un fallo del objeto con efectos desastrosos en el entorno. Simbólicamente hay tres grupos de factores de riesgo:

- Factores físico-geológicos internos en fundación de la presa y en el cuerpo de la presa provocando su inestabilidad.
- Factores hidrogeológicos e hidrológicos dentro de un área de influencia.
- Procesos glaciológicos y termodinámicos.

Este análisis se llevó a cabo mediante la evaluación del desempeño ambiental Norma Internacional ISO 14031 y Evaluación de Riesgos Ambientales, de marzo de 1999. Para llegar a cuantificar los riesgos de cada uno de estos casos, es necesario identificar y familiarizarse con los accidentes con mayor frecuencia e identificada a partir de las fuentes históricas que iniciaron estos accidentes (iniciadores). Con estos accidentes recreados en un árbol de eventos; por el que se evalúan las posibles consecuencias relacionadas con el fracaso en una simulación de la alteración del proceso, los árboles de sucesos utilizan un análisis prospectivo (a partir de un suceso iniciador es posible determinar sus consecuencias).

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ABBREVIATIONS

A	a.s.l.	Absolutely see level
	ASTER	Advanced Space-borne Thermal Emission and Reflection Radiometer
B		
C	CAIAG	Central Asian Institute of Applied GeoScience
D	DEM	Digital Elevation Model
E	EGP	Exogenesis geological processes
	ET	Event tree
F	FMEA	Failure Modes and Effects Analysis
	FMECA	Failure Modes and Effects Critically Analysis"
G	GLOF	Glacier Lake Outburst Flood
	GIS	Geoinformation system
H	HFA	Hyogo Framework for Action
	HL	Human life
I	IE	Initiating event
K	KR	Kyrgyz republic
N	NE	Natural environment
S	SFIT	Swiss Federal Institute of Technology
	SE	Socioeconomic
	SRTM	Shuttle Radar Transmission Mission
T	TMF	Tailing management facility
	TTS	Temporary Technical Secretariat
U	UN	United Nations
W	WGI	World Glacier Inventory

1. INTRODUCTION

1.1 Background

Natural hazards and dangerous geological events are common throughout the Tien-Shan Mountains which are characterized by very diverse landscapes, ecological and climatic conditions and geological environments, and by intense geodynamic activity. The most destructive natural hazards are earthquakes, landslides, rockslides, mountain lake outburst floods, and mudslides. Natural and man-made hazards resulting from climate change and strong anthropogenic impacts on the mountain environments have become widespread in the Tien Shan in recent 10-15 years and intensified "common" exogenetic geological processes (EGP) and triggered new ones. Among the natural and man-made hazards the biggest perils are induced seismicity, water logging, glaciers and permafrost degradation, cryogenic processes, accidents at large engineering facilities (open pits, tailing dumps, dams, etc.). There is an assessment of climate change impacts on the natural and man-made hazards intensification in the mountainous regions of Kyrgyzstan below.

In according to the information from the KR Ministry of Emergency Situations, from 2000 to 2008 the average number of yearly natural disasters and emergency situations of geological origin (earthquakes, mudslides, landslides) was 76, which is 1.2 times greater the average number of natural disasters that occurred between 1990 and 1999 and 1.6 times greater as compared to the period from 1980 to 1989. For example, in 1990-1999, 297 mudslides were reported whereas in 2000-2013 there were 368 mudslides. It is worthy of note that the period from 1997 to 2007 was the warmest period on record, and in 2000-2013 the average annual temperature was 0.2°C higher than in the 1990-s. Therefore, we have reasonable grounds to believe that the number of natural and man-made hazards increased as a result of climate changes in the Tien Shan Mountains.

One of the hazardous consequences of climate warming is the degradation of glaciers and permafrost followed by glacial lake outburst floods, mudslides and other EGP. In the late 20th century, the Kyrgyz Tien-Shan contained 5,237 glaciers covering the total area of 6,336 km^2. Fresh water contained in those glaciers whose runoff makes up 30-50% of the total summer river runoff in mountains is the most essential natural resource of not only Kyrgyzstan but the entire Central Asia. As the climate products and the unique indicators of climate changes, the glaciers react to any changes in air temperature and humidity.

Also, widespread glacier recession leads to formation and/or expansion of glacial lakes that may burst as the result of continuing climate warming and rapid melting of their ice dams.

The Petrov's Glacier, which is the largest glacier in the Naryn (Syrdarya) River Basin, has been rapidly recessing in the recent years as dust coating from blasting operations at the Kumtor Mine accelerated its natural melting. Glacier retreat is followed by expansion of the Petrov's Lake that may end in a lake outburst flood due to the buried glacier ice melting in the lake moraine dam.

As a result of glacier recession, the lake volume increased from 23.1 million m^3 in 1978 to 105.8 million m^3 in 2013. The release of such water amount can have disastrous consequences. In particular, the hydrodynamic wave can destroy the tailings dump located downstream the Kumtor River (which is the head of the Naryn River) and containing 43 million $m^3$of cyanide bearing wastes.

The situation gets even worse as due to rapid melting of frozen loamy soils in the bottom of the tailings dump, the dam that holds the tailings began deforming and moving. In the worst case scenario (an earthquake followed by collapse of the glacier and/or opening of cavities within the glacier or ice dam), a local glacial lake outburst flood may lead to contamination of the Naryn River Basin with toxic wastes thus posing a danger for the whole region. To prevent a catastrophic outburst flood event, the water level in the Petrov's Lake and the moraine-ice dam are monitored constantly and technical proposals on how to decrease the water level are being developed.

From the experience of the Kumtor Gold Project (3,700-4,200 m a.s.l.), out of all other components of the mountain zone, permafrost is the most prone to the climate warming. Human activity triggers permafrost degradation and thus causes drastic and irreversible changes in its physical (strength, deformation, thermal physics, filtration, etc.) and geotechnical (bearing capacity, subsidence, etc.) properties. At the Kumtor Gold Mine such changes in the properties and cryogenic structure of permafrost finally led to the tailings dam deformation and movement, thermal erosion and subsidence followed by water seepage in areas with the drainage and diverting ditches, solifluction and creep processes on slopes undercut by roads and the pulp line, ground subsidence under buildings and structures, and landslides and rock slides in the open pit resulting in considerable economic loss and people death.

The above examples of increasing danger and risks and natural and man-made hazards highlight the importance of monitoring climate changes and mining activity in high mountain regions and forecasting changes in geotechnical and ecological conditions and potentially dangerous in geodynamically active regions of the Tien-Shan. Otherwise, the continuing global warming may trigger catastrophic processes on a regional scale.

1.2 Research Goals and Objectives

The present study had two main objectives:

a) to analyze of risk to Glacial lake outburst flood GLOF hazards in a Petrov's Lake,
b) in particular, due to risks of accident at tailings pond (waste mining) by glacial lake outburst flood in the territory of The Kumtor active gold-mining company (Kyrgyz Republic) and
c) to develop recommendations for adaptation to, and mitigation of hazards;

This three-fold objective requires both an assessment of the extent to which specific glacial lakes are unstable, and an analysis of the degree to which people and property downstream are vulnerable. This work will contribute to the study of an overall strategy for risk management which will include a more precise identification of the hazard as well as early warning and mitigation measures. As the physical attributes of Petrov's glacial lake are similar throughout the Tian-Shan region.

2. GLACIER LAKES OF KYRGYZSTAN

2.1 General information about glaciers of Kyrgyzstan

Tien Shan is one of the largest mountain systems in Asia stretching 2,000 km from west to east between $36 - 40^0$N and $69 - 95\ ^0$E. Glaciers of Tien Shan (Figure 2.1) spread in altitudinal belt between 2,800 m a.s.l. and 7,400 m a.s.l. and inters one of the major sources of water in central Asia endorheic basins feeding the Aral-Caspian, Balkhash, Issik Kul, and Tarim hydrographic systems. The glaciers of Tien Shan are supplying water for approximately 50 million populations of Kyrgyzstan, Uzbekistan, Kazakhstan, northern Tajikistan, and Xinjiang supporting the low lands agriculture, urban, and industrial areas. Most of which are located on the territory of Kyrgyzstan.

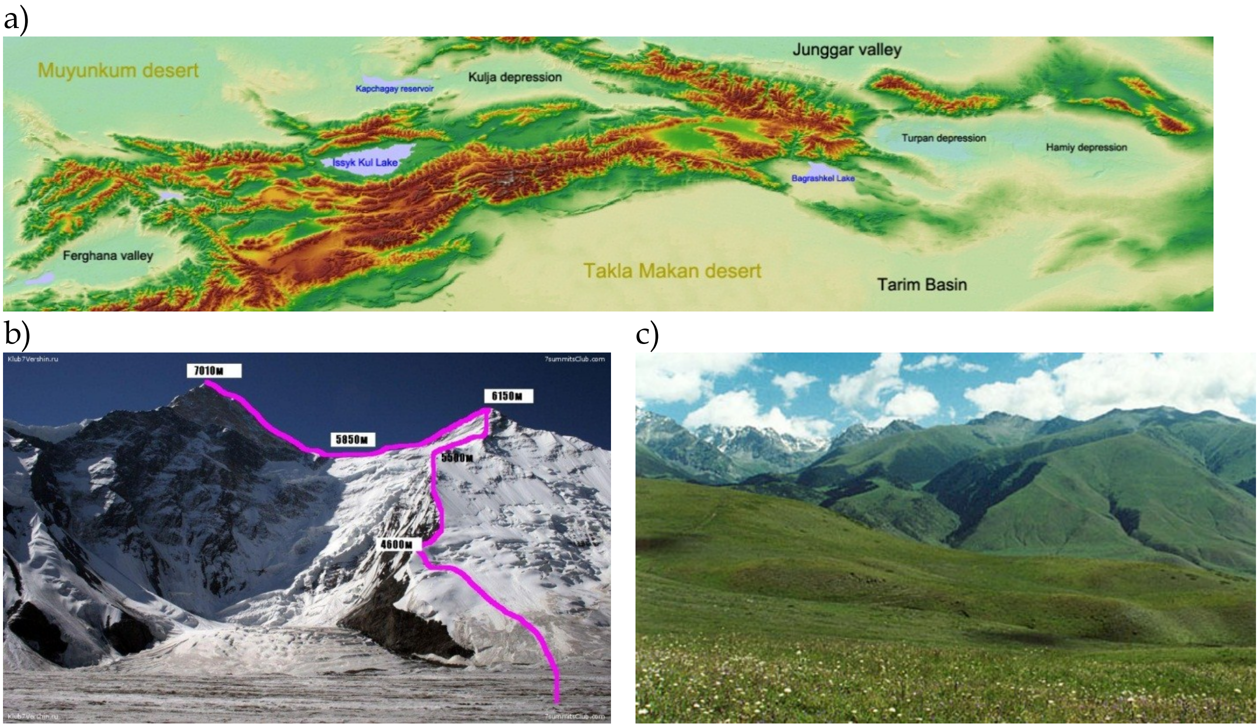


Figure 2.1 Tien Shan Mountains: **a)** Tien Shan mountain system in space image; **b)** Khan Tengri Peak (kaz. "King Heaven") is located on the China—Kyrgyzstan—Kazakhstan border; **c)** Foothills of the Tien Shan.

The latest investigations over the whole mountains on the territory of Kyrgyzstan based on remote sensing data numbers 7,590 glaciers with total area of 8100 km^2 (about 30% of the total land area of the Kyrgyz Republic) and 1,840 km^3 volume of ice. There are different types of glaciers in Kyrgyzstan, from large valley and dendrite glaciers, prevalent in central Tien Shan, to small lobes, niche glaciers in all Tien Shan alpine areas. Large valley glaciers form 82% of the Tien Shan total glacier area. The glaciers themselves cover about 4% of the surface area of the country.

The most famous is the Enilchek Glacier – actually there are two branches –Northern and Southern in the Peak Pobeda (7439 m), Khan Tengri (6995 m) massif in the Eastern Tien Shan.

Some glaciers are within easy reach of Bishkek, (for example the Ak Sai (3500 m) and Adygene (3200 m) in Ala Archa National park), and several companies offer two or three day treks to them.

Here is a list of some of the major glaciers to be found in the republic. Different sources sometimes give different figures for their length and area – possibly a sign of the effects of climate change.

Table 2.1 Main glaciers on the territory of Kyrgyzstan.

Glacier	**Location**	**River**	**Length (km)**	**Area (km^2)**	**Altitude (m)**
Southern Enilchek	Pobeda/Khan Tengri	Enilchek	60.5	632.3	908
Northern Enilchek	Pobeda/Khan Tengri	Mezebacher Lakes	32.8	215.2	1040
Kayingdi	Pobeda/Khan Tengri	Kayingdi	29.0	97.2	1040
Korjinevskovo	Zapaiski Ridge	Djanai Dartak	21.5	99.4	1885
Mushketova	Pobeda/Khan Tengri	Arir Ter	20.5	71.3	1050
Semyenova	Pobeda/Khan Tengri	Sary Jaz	20.2	64.5	1020
Lenin	Lenin	Achik Tash	13.5	58.1	1150
Mushketova	Kakshaal	Kotur	13.3	23.0	1200
Nalivkina	Kakshaal	Ai-Tala	13.2	19.5	1210
Keikal	Pobeda/Khan Tengri	Terekti	12.9	26.8	1030
Petrov’sa	Ak Sheirak	Kumtor	14.3	73.9	1010

2.2 Mapping of Glaciers and Glacial Lakes of Kyrgyzstan.

- **Mapping Glaciers**

The methodology used for mapping Kyrgyzstan's glaciers follows the recommendations developed for the World Glacier Inventory (WGI) by Müller at the Temporary Technical Secretariat (TTS), Swiss Federal Institute of Technology (SFIT), Zurich.

The attributes of glaciers used in mapping are as follows:

1. Unique identifier (basin and sub-basin name, glacier name, latitude, longitude, and highest, lowest, and mean elevations)
2. Physical parameters (area, length, and orientation of glacier)
3. Glacier type (class)
4. Source of database and date

Ideally, glacier information should be compiled from a single source over a narrow temporal range. This opportunity was offered more closely when images became available from Landsat, 7, since these have a narrower temporal base (2005±3 years). These images were used to prepare a new inventory, which therefore provides a more accurate base for analysis. Furthermore, the new mapping process was undertaken by applying a Arc Map software to delineate glacier boundaries.

The 1987 inventory identified 6771 glaciers in Nepal covering an area of 8009,4 km^2. The new inventory prepared using the Landsat 5 and 7 images mapped 5237 glaciers with a total area of 6336 km^2 (Figure 2.2 and Table 2.2)

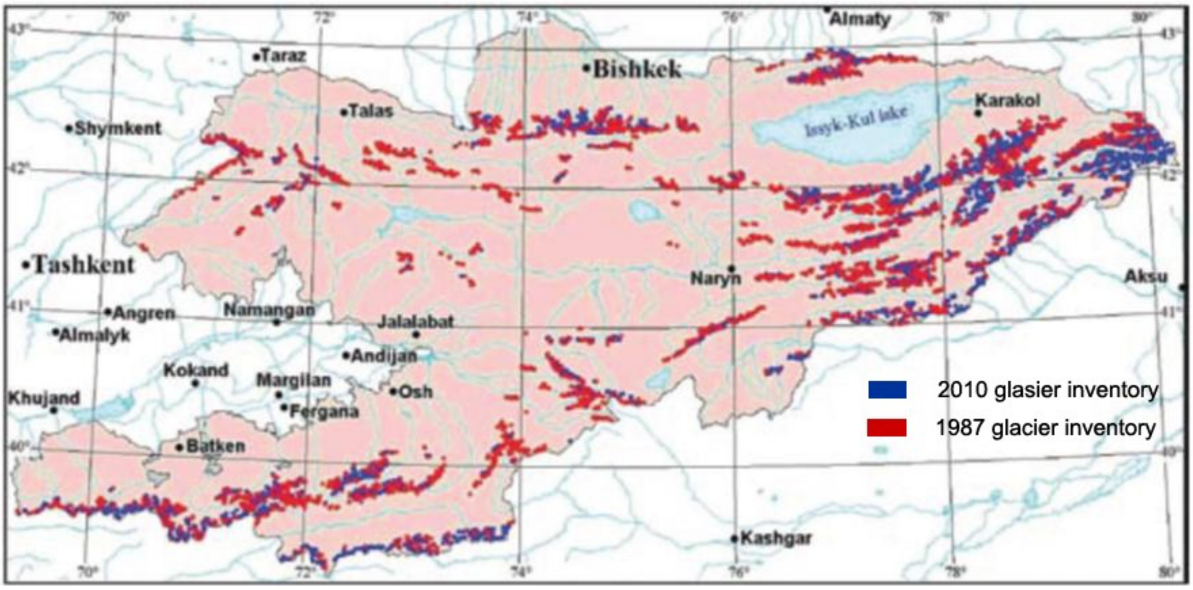


Figure 2.2 Comparison of the number of glaciers of 1987 and 2010 inventory

Table 2.2 Distribution of glaciers in the Kyrgyzstan Mountains.

	1987 glacier inventory		**2010 glacier inventory**	
Range	**No. of Glaciers**	**Total Area (km^2)**	**No. of Glaciers**	**Total Area (km^2)**
Tien Shan	5329	6298,4	3836	4660
Pamir Alai	1442	1711	1401	1676
Total	**6771**	**8009,4**	**5237**	**6336**

- **Mapping Glacial Lakes**

For the inventory, glacial lakes were defined as all lakes in a river basin that lie above 3,500 m, and are fed by glacial melt (Figure 2.3). The altitude was selected as representing the approximate lower limit of glacial moraine accumulations in Kyrgyzstan. Glacial lakes may also exist beneath or within glaciers, but these are not usually visible on aerial images and so cannot be mapped. Thus such lakes were not included.

Information on the elevation of the glacial lakes was derived from the Shuttle Radar Transmission Mission Digital Elevation Model (SRTM DEM) and Advanced Space-borne Thermal Emission and Reflection Radiometer (ASTER) Global DEM. This data source was used to detect the boundaries of glacial lakes and to help classify them. Google Earth satellite images were used to verify the glacial lake inventory data. A combination of open source remote sensing and GIS software packages, such as Google Earth, were used to edit, manage, and analysis the data.

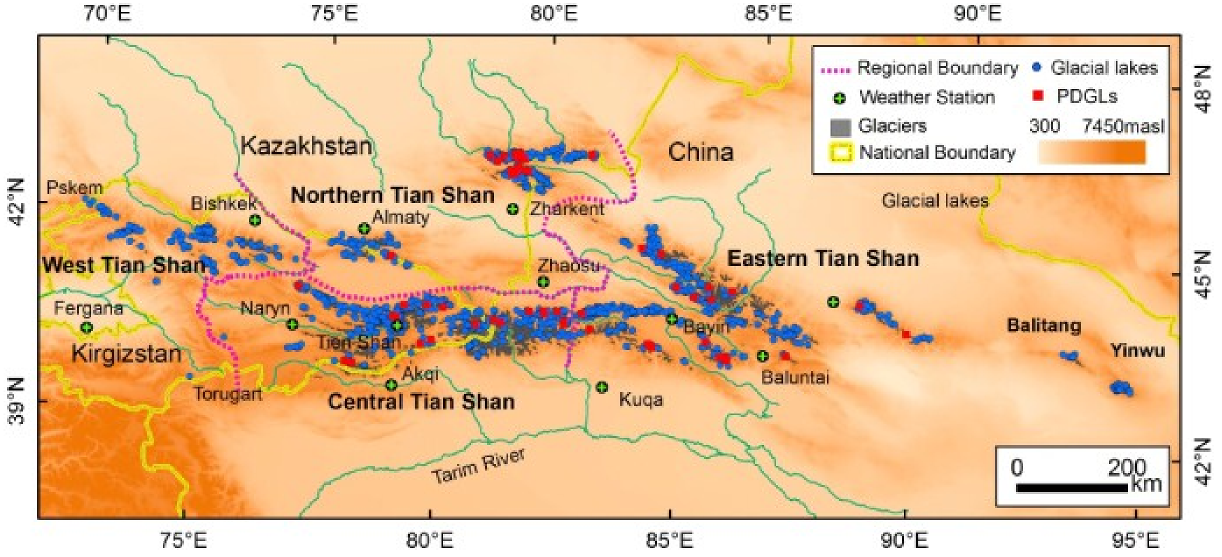


Figure 2.3 Location of glacial lakes in Tien Shan

Detection of glacial lakes

Detection of glacial lakes using multispectral imagery involves discriminating between water and other types of surface. Delineation of surface water can be achieved using spectral reflectance differences. Water strongly absorbs light in the near- and middle-infrared wavelengths (0.8 – 2.5 µm). The Normalized Difference Water Index (NDWI) was used for automated glacial lake detection followed by visual interpretation. DEM and Google Earth were used for better visualization, especially for lakes in shadow and/or snow-covered areas (Figure 2.4).

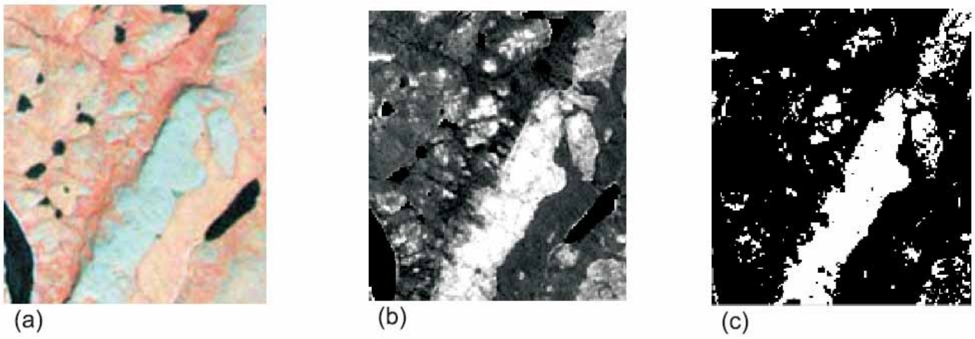


Figure 2.4 Example of glacier map derived from ASTER data. a) ASTER colour composite image (4,3,2 - RGB) red is ground and cyan is glacier b) Ratio image of bands 7 and 4 enhance glacier (based on difference in spectral reflectance) which are the white areas c) glacier map

2.3 Formation of glacier lakes.

Glacier-dammed lakes form in a number of different situations. The largest lakes, which present the greatest hazards, occur in ice free tributary valleys blocked off by active valley glaciers. Most common are small lakes situated in alcoves and niches in the valley walls along the margins of glaciers and in depressions formed where tributary valley glaciers join. A few lakes are located slightly above the regional firm line; the large majority occurs along the lower reaches of glaciers.

Intensity of ice thawing sharply increases in such conditions and glacial waters volume increases.

Closing off of water way by a glacier it begins to fill with melt water and rain water from the surrounding basin. The resulting lake continues to fill until the water overflowing or initiates a dumping process at the ice dam. Filling continues at a reduced rate during the winter by water draining from the porous old snow in the higher areas of nearby glaciers. Winter snowfall also adds to the lake height.

2.3.1 Types of glacier lakes

In Kyrgyzstan, the last decade has been formed hundreds of glacial lakes. Annual increase in temperature, also the impact of human factors leads increase in the volume of glacial lakes and their possible outburst floods.

The glacial lakes were classified broadly into moraine-dammed, ice-dammed, erosion, and other lakes. The detailed classification is summarized in Table 2.3 and Figure 2.5 Some of the more common types of lake in Nepal are described in the following.

- *Moraine-dammed lake*: As a glacier tongue thins and retreats, meltwater can become trapped in the trough between the glacier terminus and its end moraine. Lakes may also accumulate along the glacier margins, between the lateral moraine and the valley side. Depending on the topography of the glacial foreland inside the end moraine, small lakes may also accumulate in the numerous depressions that are characteristic of the terrain.

- *Supra-glacial lakes*: The only ice-dammed lakes identified in Nepal are supra-glacial lakes. The recent period of atmospheric warming has caused many of the glaciers in the Nepal Himalayas to thin. The lower tongues of a large number of these glaciers are almost completely mantled with morainic debris and rock fall from the surrounding valley walls. In the early stages of down melting, small ponds accumulate within the surface moraine. These ponds are inherently unstable and may drain glacially or through a lateral moraine before reaching significant dimensions. In many cases, however, they have grown in size as glacier melt continued, and have amalgamated into progressively larger supra-glacial lakes. While most of these lakes originate as small ponds, their progressive expansion has produced some of the largest of the Himalayan lakes. As lake expansion and glacial retreat continue, these supra-glacial lakes may merge with end-moraine dammed lakes. Because of the enormous volume of such lakes, they are often perceived to be among the most critical.

- *Erosion lakes:* Glacial erosion lakes are bodies of water that form following glacial erosion and “over-deepening”. They exist in a variety of forms such as in depressions formed by cirque glaciers and as glacial valley lakes that accumulated in depressions after the eroding glacier retreated or disappeared. They may be partially dammed by very old end moraines. They have usually been in existence for hundreds or even thousands of years

- *Other glacial lakes:* Rock falls, debris flows, and landslides often send masses of rock and soil debris on to valley floors damming local streams originating in glaciers. Bodies of water may also form amongst the uneven hummocks created by these deposits.

Table 2.3 Classification of glacial lakes.

Glacier lake type	**Definition**	**Notes**
Moraine-dammed lake	Lake dammed by moraine following glacial retreat	
End-moraine dammed lake	Lake dammed by end (terminal) moraines	Usually touches the walls of the side moraines, but the water is held back by the end moraine (dam), lake usually, but not necessarily, in contact with the glacier, and may have glacier ice at the lake bottom (defined in some other classifications as "advanced form of supra-glacial").
Lateral moraine dammed lake (ice free)	Lake dammed by lateral moraine(s) not in contact with glacial ice	Lake is held back by the outside wall of a lateral moraine, i.e., away from the formerglacial path; lake may be in the fork formed between two lateral moraines of a main glacier and a glacier in a tributary valley; 'ice free' means the lateral moraine itself is no longer in contact with the glacier.
Lateral moraine dammed lake (with ice)	Lake dammed by lateral moraine(s) in contact with glacial ice	As above, but the lateral moraine is in contact with the glacier ice.
Other moraine dammed lake	Lake dammed by other moraines (includes kettle lakes and thermokarst lakes)	
Ice-dammed lake	Lakes dammed by glacier ice	
Supra-glacial lake	Pond or lake on the surface of a glacier	Most common type of ice-dammed lake in the Tien Shan region
Glacier ice-dammed lake	Lake dammed by glacier ice with no lateral moraines	Dammed by the glacier ice, with no lateral moraine; can be at the side of a glacier between the glacier margin and valley wall.
Glacier erosion lake	Bodies of water that form as a result of an earlier glacial erosion process, which accumulate in depressions after the glacier has retreated or melted away	
Cirque lake	A small pond occupying a cirque	
Glacier trough valley lake	Lakes formed in the glacier trough as a result of the glacier erosion process	For example ribbon lakes

Other glacier erosion lake	Bodies of water occupying depressions formed by the glacial erosion process; these are usually located on the mid-slope of hills, but not necessarily in a cirque.	
Other glacial lakes	Lakes formed in a glaciated valley, and fed by glacial melt, but damming material not directly part of the glacial process	
	Debris-dammed lake	Lake formed by dam following a debris fall, rock avalanche, or landslide in a glacial valley and fed by glacial melt
	Artificial lake	Lake formed by a man-made dam in a glacial valley and fed by glacial melt
	Other lakes fed by glacial melt	

Figure 2.5 Classification of glacial lakes; **a)** end moraine-dammed lake; **b)** lateral moraine dammed lake (ice free); **c)** lateral moraine dammed lake (with ice); **d)** supra-glacial lake; **e)** glacier ice-dammed lake; **f)** cirque lake; **g)** glacier trough valley lake; **h)** debris-dammed lake; **i)** artificial lake.

In Kyrgyzstan, over 200 glacier lakes exist, of which about 10 have been classified as hazardous. The largest lakes are the Merzbacher, Petrov's and Ala-Archa lakes, which are situated at an altitude between 4,000 and 4,500 m. In the Kumtor valley, the height of the valley floor decreases from 4,500 m to 3,600 m. It's vertical distance of only 20 km, which provides a rather steep angle of slope and high erosional flow velocities of potential floods.

2.4 Potential hazards by glacier lake outbursts

Among glacier hazards, glacier lake outburst floods (GLOF) possess the most far impact zone. The devastating effect itself is significantly dependent from the peak discharge, which is in general much higher than that of floods triggered by rainfall or snowmelt.

From the historical record, glacier hazards are comparatively well described from the European Alps, where during the Little Ice Age (1600–1850) especially advancing tributary glaciers have dammed the main valley (e.g., impoundment of the Saaser Vispa by the Allalin glacier).

The general glacier melting around the world during the twentieth century has led to a shift in the glacial systems and therefore in the glacial hazard potential. The glacier retreat has become obvious in the accelerated formation of moraine-dammed lakes in the Himalayas since 1950s and the Peruvian Andes. With the augmented settlement density in high mountain regions, the hazard potential has increased in some areas. This is especially true for valley settlements that are dependent on the irrigation of glacial melt water.

In the Kyrgyzstan glacier hazards have reached a wider recognition by the outbreak of the Yashylkol in the Isfayram Say July 18, 1966. The lake outburst has been triggered by an ice avalanche, falling into the lake and caused a high flood wave. This type of Lake Outburst may be one of the major hazards in high mountain areas in the future. A lot of glaciers are in the transition from small-sized valley glaciers, reaching just the foot of the mountain, to hanging glaciers. However, most of the settlements in the Tian Shan are located at the slopes or even on mountain ridges, in a rather flood location. The main hazards are generated by the outburst of glacier-dammed lakes. Moreover, their formation and outburst is highly unpredictable. Glacier advances in this region would lead to an increase in glacier-dammed lakes and in turn to a higher hazard potential.

2.5 Glacial Lake Outburst Floods (GLOF)

A glacial lake outburst flood (GLOF) is a type of outburst flood that occurs when the dam containing a glacial lake fails. This is also called by its Icelandic name, "*Jökulhlaup*". The dam can consist of glacier ice or a terminal moraine. Failure can happen due to

erosion, a buildup of water pressure, an avalanche of rock or heavy snow, an earthquake, volcanic eruptions under the ice, or if a large enough portion of a glacier breaks off and massively displaces the waters in a glacial lake at its base.
According to the information, Kyrgyzstan has experienced at least 18 GLOF events in the past. Of these, 10 are believed to have occurred in Kyrgyzstan itself, and 8 were the result of flood surge over spills across the China border (Figure 2.6, Table 2.4).

Among the 10 GLOF events known to have occurred in Kyrgyzstan, one took place in the distant past; five of recent date are quite well recorded; and eight of indeterminate date and two of recent date were recorded as occurrences, but without details of the losses incurred.

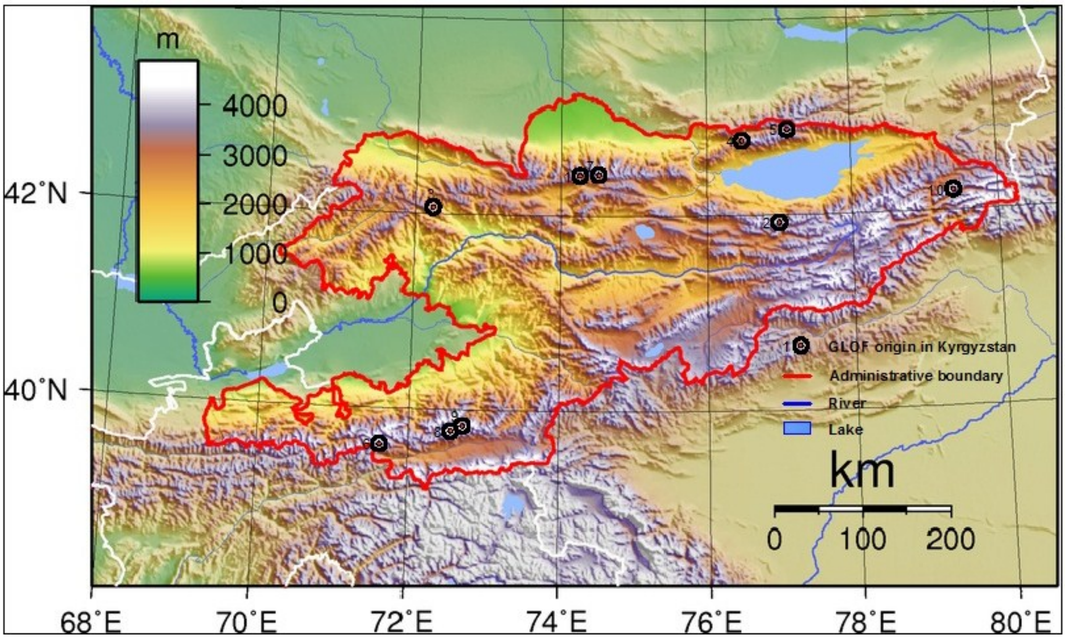


Figure 2.6 Location of GLOF events caused damage in Kyrgyzstan

Table 2.4 GLOF events recorded in Kyrgyzstan.

	Date	River basin	Lake	Cause	Losses
Entirely within Kyrgyzstan					
1	21.07.2012	Ala Archa	Tez Tor	Moraine collapse	Not Known
2	20.07.2008	Ton	Zyndan	Moraine collapse	3 Human lives, bridges, others
3	05.07.2007	Jeruy	Jeruy	Moraine collapse	Not Known
4	01.07.2005	Nooruz	Takyr Tor	Moraine collapse	Human lives, bridges, others
5	16.05.2005	Issyk	Issyk	Moraine collapse	Not Known

6	18.07.1966	Isfayram Say	Yashylkul	Moraine collapse	Human lives, bridges, others
7	Unknown	Chuy	Almatinka	Moraine collapse	Not Known
8	Unknown	Alay	Rankul	Moraine collapse	Not Known
9	Unknown	Alay	Shor Kul	Ice avalanche	Not Known
10	Unknown	Sary Jaz	Arun	Ice avalanche	Not Known

Zyndan (20 August 2008)
This event was investigated by based on digital processing of Landsat satellite data, also was writed a detailed article. However, there is some disagreement between the two about both the cause and manner of the actual outburst and the total volume of water released.

Yssyk (16 May 2005)
A GLOF event in the Issyk basin occurred due to the collapse of a moraine in the Issyk river basin. This lake has since reformed to a critical level and is thus included in the potentially dangerous category.

Yashylkul (18 July 1966)
The Yashylkul GLOF is the most dangerous event of its type in Kyrgyzstan. Thus only the most salient points are discussed here in a little more detail.

Takyr Tor Lake (01 July 2005)
Takyr Tor Lake discharged when its end-moraine dam collapsed. Few details are available although it is known that some houses were destroyed and some farmland was torn away.

Jeruy (05 July 2007)
This GLOF was triggered when an ice avalanche hit the frontal lake and induced a surge wave which overtopped the end moraine dam.

Tez-Tor lake(21 July 2012)
The GLOF event occurred on the Ala-Archa River from Tez-Tor lake as a result of moraine collapse: details of the damage are not known.

Others
In addition to the events described above, four GLOFs have been identified in Kyrgyzstan from analysis of geomorphological features seen on satellite images and aerial photographs. Precise dates and details of the events are not available; however all are known to have occurred when the end moraines collapsed. Two events were identified in the Alay basin; one in the Sary Jaz; and one in the Chuy.

Some events have led to substantial economic losses, for example Zyndan Lake outburst in Ton region (Kyrgyzstan) 2008. For the majority of mountain glaciers around the world, recent decades have been characterized by an increasingly negative glacier mass balance and consequent glacier shrinkage and termini retreat attributed to rapid climatic warming. Projections of future climate indicate that this trend will continue. The observed and projected data shows a accelerating glacier lake formation. The number, area and volume of hazardous glacier lakes are increasing in mountain areas. This process combined with increasing land use activity in some mountain areas could lead to extensive damage and significant life loss in the case of unexpected GLOFs.

Recent studies of glacier lakes have been focused on lake detection using satellite/aerial imagery. They were helping to determine outburst mechanisms, dam stability assessment and outburst flood modeling. Simple techniques to determine glacial lake outburst probability and to assess possible outburst flood distances 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 behavior 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.

2.6 Trigger mechanisms for glacier lake outburst flood (GLOF)

The failure of dams occurs through a variety of different mechanisms:

1. A very common outburst mechanism is the generation of displacement waves generated by ice avalanches or rock fall into the glacier lake. Subsequently, the flood creates a characteristic V-shaped incision into the moraine (Figure 2.5.b) or surges through an existent outlet channel and widens it rapidly. The natural spillway may be enlarged subsequently by retrogressive erosion.

2. Glacier may induce displacement waves overtopping the moraine dam. At the glacier tongue, crevasses are located immediately behind the ice cliff and undercutting at the water line may accelerate the calving processes. Calving of glaciers into glacial lakes increases the lake size. Floating glacier tongues are considered to be highly dangerous. They can collapse catastrophically into the lake.

3. Damage of ice cores increases the volume of the lake and poses a serious risk to dam stability.

4. Earthquakes may lead to a dam failure by mass movement and destabilization of the dam.

5. The moraine dam may gradually become instable by infiltration, and the enlargement of drainage conduits in the moraine. This natural process is sometimes accelerated accidentally by artificial drainage measurements and leaking of the pipes.

6. Catastrophic sub or englacial drainage of the glacier tongue area into the moraine-dammed lake may lead to a sudden rise of the water level in the glacial lake.

7. Heavy rainfall or snow melt may increase the lake level abruptly and lead to an outburst.

2.7 Hazard and Risk

For GLOF events, the risk needs to be defined in relation to the people and property located downstream. This is by no means easy because the phenomenon that leads to the risk is extremely difficult to predict. It is also important to note that 'at risk' modern developments such as hydroelectric facilities, tourist hotels and tea shops, bridges, and roads have increased in number over the last twenty or more years and will continue to do so. Thus the scale of the risk envisaged is increasing.

In general terms, risk is defined as a combination of the consequence and probability of the threatening event (the hazard) in relation to the vulnerability of the people and property that may be affected by the event. The *Joint Technical Committee on Landslides and Engineered Slopes* (JTC1) has defined risk as a 'measure of the probability and severity of an adverse effect to life, health, property, or the environment' (JTC1 2004). Thus, natural risks consist of two components: the hazard, i.e., the probability of a major natural event happening, and the severity, i.e., the potential casualties and/or damage. In simple terms;

$$\boldsymbol{Risk} = \boldsymbol{Probability} \times \boldsymbol{Severity}.$$

Probability is defined as a "natural phenomenon that could lead to damage, described in terms of its geometry, mechanical, and other characteristics".

Consequence is the outcome of an event and has an effect on objectives. A single event can generate a range of consequences which can have both positive and negative effects on objectives. Initial consequences can also escalate through knock-on effects. In the case of GLOFs, however, very few have ever occurred, either in Kyrgyzstan or in the neighboring mountains of China or Tajikistan, and repeat discharge from a single source is particularly rare. Often, once a moraine-dammed lake has burst, the process dismantles the end moraine to such an extent that the danger of a subsequent discharge is either minimized or eliminated.

Severity is usually the simplest part of the equation. It can be determined in two steps:

1. Take a worst-case scenario of a lake outburst and determine the surface perimeter that would be affected below the source.

2. Compile the statistics for population and property located within the perimeter and calculate the value, assuming total loss.

2.8 Problems in investigating in Kyrgyzstan.

In the thesis we estimate the probability as well as the magnitude of potential GLOF events. This task is very difficult since the probability of a lake outburst cannot be predicted with any reasonable level of certainty. This introduces another dimension of the problem, that of perception or what people who live downstream from a glacial lake think about the impending threat. This is a considerable problem because, over the past twenty years or so, exaggerated reporting in both the news media and the semi-scientific literature, and widespread reaction to it, have influenced this perception.

Need to analyze and to determine GLOFs have occurred in the recent past, they have taken lives and destroyed property, and there is no doubt that such catastrophes will occur in the future, if not tomorrow. The difficulty lies in balancing all of these elements as well as estimating the costs of any mitigation efforts and/or early warning systems. When only limited resources are available, it is important to have a clear perspective of costs and benefits.

2.9 Risk Management and Strategy in Kyrgyzstan

Glaciers and glacial lakes in the territory of Kyrgyzstan have been categorised and mapped systematically; nevertheless there are prevailing risks. Increased human pressure in high mountain areas and growing socioeconomic vulnerability mean that GLOF risk management is needed.

Risk management is defined as “the creation and evaluation of options for initiating or changing human activities or (natural and artificial) structures with the objectives of increasing the net benefit to human society and preventing harm to humans and what they value; and the implementation of chosen options and the monitoring of their effectiveness”

In May 2011, in Geneva, Switzerland at the third session of the Global Platform for Disaster Risk Reduction, the World Conference on Disaster Risk Reduction Ministry of

Emergency Situations of the Kyrgyz Republic was announced the establishment of a National Platform for Disaster Risk Reduction in the Kyrgyz Republic.

The Government of Kyrgyz Republic is develops a "National Platform of Kyrgyz republic of disaster risk reduction" with the support of UNDP "Disaster Risk Management". This has improved understanding and capacity in hazard assessment and mapping of recurring disasters and a component on disaster risk reduction has been included in national development plans. The Tenth Five Year Plan (2005-2015) incorporated disaster risk reduction and preparedness and mainstreaming of components. Kyrgyz Republic has also ratified the Hyogo Framework for Action (HFA) 2005-2015, adopted at the UN World Conference on Disaster Reduction, Kobe (Japan), in 2005.

A qualitative change is visualized in this strategy document based on realization of the need to mainstream disaster risk management into development activities and to shifting the emphasis from relief to preparedness. The document also proposes an organizational set up for a "Interdepartmental Commission for Civil Protection" chaired by the Prime Minister of the Kyrgyz Republic for Integrated safety of the population and territory of the Kyrgyz Republic in emergency and crisis situations until 2020. In addition, a 'Law on the glaciers of the Kyrgyz Republic' was drafted and is in the process of promulgation.

Other documents related to disaster preparedness and its policies in Kyrgyz Republic include the following:

- National Plan of Action to Combat Desertification in the Kyrgyz Republic. http://www.unccd.int/ActionProgrammes/kyrgyzstan-rus2000.pdf

- Water Code of the Kyrgyz Republic http://online.adviser.kg/Document/?doc_id=30299858

- National Sustainable Development Strategy of the Kyrgyz Republic for the period 2013-2017 years http://mes.kg/ru/RNSYr/

3. INVESTIGATION OF PETROV'S LAKE

3.1 Field Investigations

One of the high priority lakes was subjected to intense field investigation in this thesis. The physical conditions, natural and technological risks and the potential socioeconomic impacts that would result from a possible lake outburst were investigated. This included topographical mapping, hydro meteorological observations, and engineering geological, geophysical, and glaciological research. Potential downstream impacts were estimated using flood-outburst modelling to show which areas would be affected in a worst case situation. This entailed mapping settlements, infrastructure, agricultural land and other features of socioeconomic significance located within the perimeter of the modelled flood limits.

3.2 Petrov's Glacier Lake

The Petrov's lake (3,741 m a.s.l.) is located in the foreground of the Petrov's glacier which is situated on the north-western slope of Ak-Shiirak massive in central Kyrgyzstan (Figure 3.1). The Ak-Shiirak massive belongs to short mountain ranges of inner Tien Shan that are elevated above wide and shallow valleys formed during the Quaternary glaciations. The region is characterized by a highly continental climate with marked seasonal variation (Table. 3.1.). In the zone of predominantly west winds, precipitation mainly falls in the spring and summer months while the winters are cold and dry. Mean January, July and annual temperatures are -11.5, -13.8, and 4.6℃, respectively, and the mean annual precipitation is 303 mm. According to meteorological data from the nearby Tian Shan station (3,614 m a.s.l.), an increase in average annual temperature of 0.009℃ has occurred during 1962–2003.

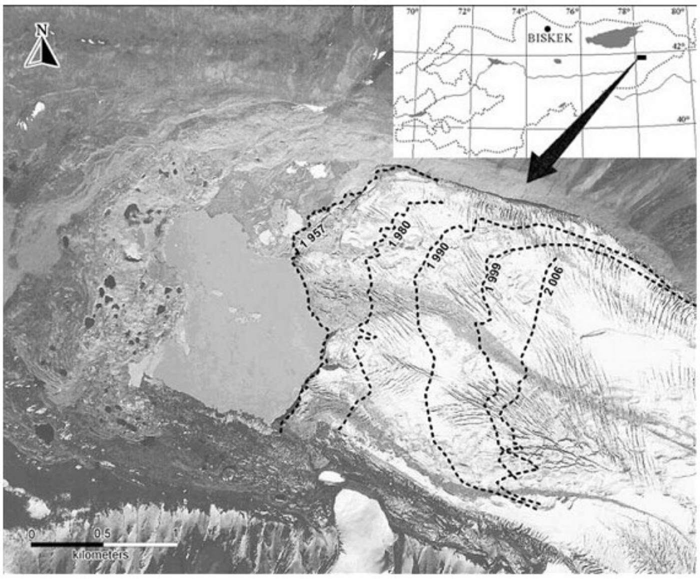


Figure 3.1 Fluctuations of the Petrov's glacier terminus since 1957.

Petrov's lake is fed by meltwater from the Petrov's glacier and small hanging glaciers in the rock walls and side valleys. The Petrov's Glacier is 69.8 km^2 in area and 12.3 km long. The terminal moraine complex that dams the lake consists predominantly of granitic material situated in the accumulation area of the glacier.

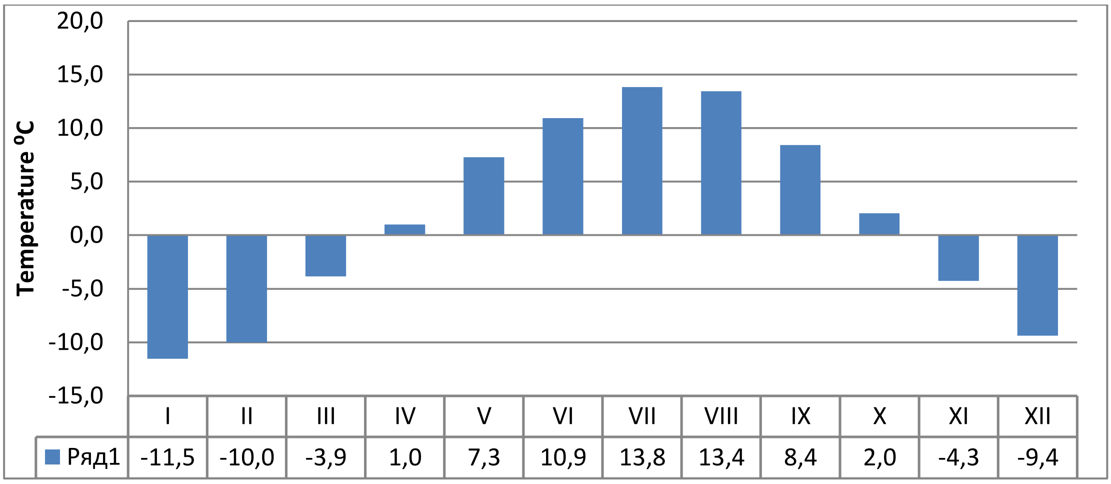


Figure 3.1 Average monthly temperatures (Tien Shan station, 1962–2013).

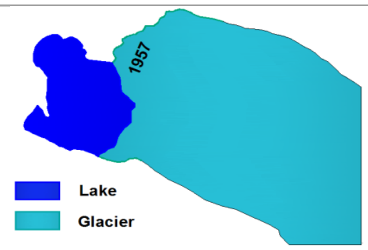
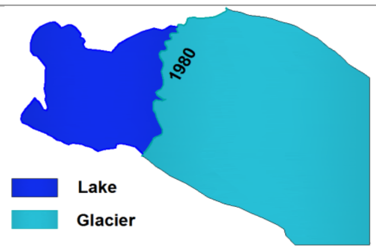
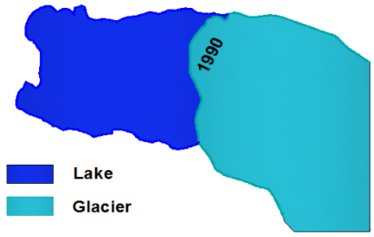
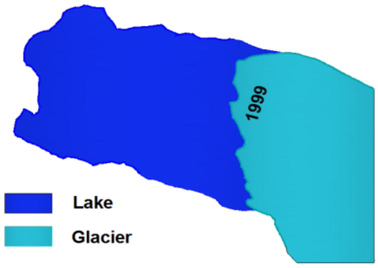
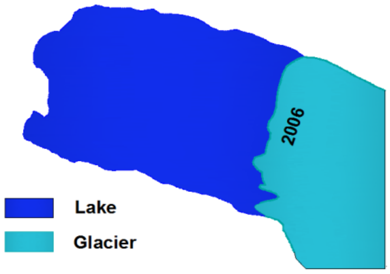
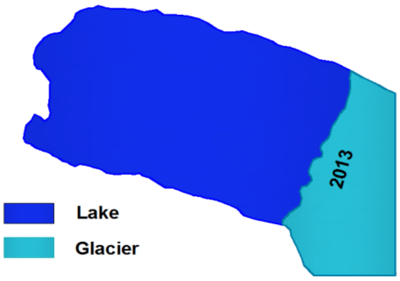
The Petrov's glacier tongue flows from the central part of the Ak-Shiirak ridge and forms the eastern shore of the Petrov's lake. In the beginning of 21 century the terminal moraine of the Petrov's glacier was accumulated at 3,710 m a.s.l. According to data a small lake appeared in front of the glacier at that time (*materials of State Agency for Cartography of Kyrgyz Republic*). Subsequent observations by Davidov (1927) indicate that the glacier terminus probably reached the morainic plain, between the terminal moraine and the western shore of the current Petrov's lake. Generic outline of the glacier position does not, however, enable determination of the exact terminus position.

3.2.1 Development of Petrov's Glacier Lake

As discussed earlier the main factor of the possibility Glacier Lake outburst failure is the possible massive melting of the glacier. With a large glacier melting, a huge volume of water entering the lake will increase the load on the moraine dam.

The survey in 1919 revealed a small re-advance of the glacier, driving the glacier terminus towards the terminal moraine of the Little Ice Age. During the 1920s and 1930s the Petrov's glacier had undergone a remarkable retreat after which another period of advance emerged during 1947–1957. The Petrov's lake had extended to approximately 0,85 km^2 between 1911 and 1947 which represents a yearly increase in surface area of 0.015 or 0,018 km^2. Volume of water in this period was equal to 14 km^3.

Table 3.1 Petrov's glaciers and lake on different periods.

Digitized map	Data
	**Lake** Area – 0.96 km^2 Annual grown – 11000 m^2 **Glacier** Total retreat – 1.330 m (1869-1957) Annual retreat – 15.1 m/y
	**Lake** Area – 1.83 km^2 Annual grown – 37600 m^2 **Glacier** Total retreat – 570 m (1957-1980) Annual retreat – 24.8 m/y
	**Lake** Area – 2.34 km^2 Annual grown – 48000 m^2 **Glacier** Total retreat – 380 m (1980-1990) Annual retreat – 38.0 m/y
	**Lake** Area – 2.80 km^2 Annual grown – 63000 m^2 **Glacier** Total retreat – 390 m (1990-1999) Annual retreat – 33.3 m/y
	**Lake** Area – 3.80 km^2 Annual grown – 92700 m^2 **Glacier** Total retreat – 430 m (1999-2006) Annual retreat – 61.4 m/y
	**Lake** Area – 4.40 km^2 Annual grown – 105.500 m^2 **Glacier** Total retreat – 470 m (2006-2013) Annual retreat – 72.3 m/y

Since the end of the 1950s till now, the glacier terminus has retreated continuously (Figure. 3.1) with an accelerating rate of recession. Table 3.1 presents the average values for linear retreat of the glacier terminus. Between 1957 and 1980 the surface of the lake increased considerably. It expanded 1.9 times, i.e. a yearly increase of the lake surface area by 0.037 km^2. The expansion of the surface has persisted. Between 1980 and 1995 the lake grew approximately 0.063 km^2 every year to reach a size of 2.78 km^2. The increase in volume was directly related to the decline of the glacier front during this same period. The increase of the lake surface correlates with an increase in volume of the lake basin.

On the basis of depth measurements in 1978 and 1995, bathymetric maps of the lake were drawn. They show that the lake basin contains two longitudinal depressions separated by shallow water back and four islands. The morphometry of the basin is related to the shaping affects of the Petrov's glacier which is made up of two main glacier bodies separated by the middle moraine which continues on the bottom of the lake basin. The deepest parts of the lake are found in front of the Petrov's glacier terminus.

Table 3.2 Rising of the lake area.

Year	Area (km^2)	Annual grown(m^2)
1911	0,2-0,3	0
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
2013	4,40	105.500

In 2006 the Petrov's glacier terminus was 1.5 km wide and more than half of it (800 m) was immersed in the lake water. As a result of the hydrostatic forces and oscillation of the water level in the lake there is intensive calving of the glacier terminus which rises up to 25 m. The falling of broken ice into the lake causes waves with the amplitude of up to 2 m, although higher waves cannot be excluded. The accelerating decay of the glacier terminus reflects the generally negative mass balance of glaciers in the Ak-Shiirak.

In 2013 area of water was 4.40 km^2 and annual grown was 105,500 m^2. The volume of water is near to the limit mark.

Experience shows that if the volume of the lake will continue to grow at such a pace that in the near future there will be a lake outburst (Table 3.2).

3.2.2 Bathymetric investigation.

The first bathymetric investigation of Petrov's lake was conducted by Kumtor operating company in 1994.

The field investigations showed that by 2012 the lake area had increased to 4.40 km^2 and the storage capacity to 105.87 km^3; the maximum depth obtained was 69.3 m. The bathymetric and topographic maps from the field survey are shown in Figure 3.2. The lake area continues to increase, but with a reduction in the rate of growth since 1957. The level differences between the benchmarks on the lateral moraines are becoming less, although not uniformly, indicating irregular settling of the surface of the moraine dam over the last seven to eight years.

The contemporary expansion of Petrov's lake is primarily towards the north as the relatively warm lake water melts back into the glacier and accentuates the collapse of blocks of ice from the cliffs that form its terminus. The southern margin of the lake close to the end moraine has also expanded, although the position of the outlet has remained more or less unchanged.

3.2.3 Hydrometeorology

The nearest hydrometeorological station "Tian-Shan", to Petrov's Lake is located about 20 km to the west and 100 m lower in elevation. The station was established in 1962 by the Department of Hydrology and Meteorology (DHM), Government of Kyrgyzstan. Hydrometeorological data were semi-automatically recorded until now and manually thereafter. Experimental measurements showed that the lake discharged at a rate of 2.9 m^3/s during the month of May with little diurnal variation. A seasonal maximum discharge of 3.7 m^3/s was observed between June and September and a seasonal minimum of 1.1 m^3/s between December and February. The discharge increased gradually from April to August and decreased from September until the onset of the winter season.

Meteorological data were obtained from the "Tian-Shan" station for the period from 1962 to 2013 (Figure 3.1). The average annual mean temperature for this period was 4.6°C; with an average annual increase of 0.009°C. August is the month with highest rainfall followed by July. The average precipitation in the area during the monsoon period (June - September) is 303 mm and during the dry season (December - February) 13.1 mm. Maximum primary and secondary solar radiation of 267 W/m^2 and 265 W/m^2 were recorded during July and May respectively.

3.2.4 Geophysical investigations

The geophysical investigations showed the existence of dead-ice blocks within the end moraine, together with multiple thermokarst features. In places the ice was visible at the surface. The presence of slowly melting blocks of ice has been corroborated by results of researching which demonstrated the presence of dead ice masses of different sizes in the end moraine. Researchers of "Kumtor" company (2010) came to a similar conclusion based on geotechnical surveys. Limited radarogram analysis based on a ground penetrating radar survey along the shoreline of Petrov's glacier lake showed that the moraine contains patches of unconsolidated materials made up of big boulders that create large voids.

The Petrov's lake is enclosed by the terminal moraine and the lateral moraines at the foot of the valley slopes. These form the shore line all the way to the current terminal moraine. While the lateral moraines are of no serious danger to the lake, the eastern and western shores are under continual development. The glacier dam on the western side of the lake is affected by the most destructive processes. It is exposed to lake level oscillations and to degradation processes in the moraine area. Among the potentially hazardous processes influencing the moraine dam through the changes of lake level are the glacier melting and calving. The estimated volumes of largest observed ice break-off exceed 500,000 m^3. Other processes such as rock or ice avalanches from adjacent rock walls and hanging glaciers could be excluded from the assessment of potential risk to the glacier dam, due to the snow and ice masses being too remote from the lake. Therefore, the hazard assessment concentrates on the Petrov's glacier and lake behavior and moraine dam properties.

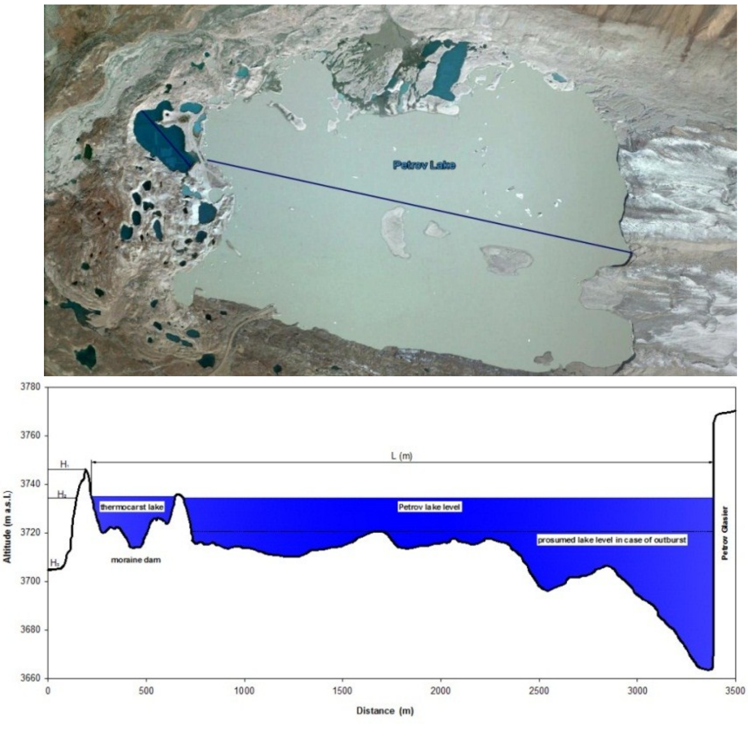


Figure 3.3 Longitudinal profile of the Petrov's Lake.

The deciding factor for the moraine dam development is the presence of buried ice which is the cause of the instability and transient lifetime of the current dam. Forming the major part of the overall moraine content, ice protrudes in many places of the sedimentary cover and represents the most dynamic part of the dam. The degradation of the dead ice is accompanied by relief sinking, thermokarst lakes emerging, morainic sediment sliding and down-slope falling. Major changes to the sedimentary cover of the dam are caused by the effect of intensive glacial processes. Many active glacial landforms are developed in the dam.

3.2.5 Glacier observations

Petrov's Lake has a wide end moraine in which there is a possibility of piping developing (formation of water channels inside the moraine due to seepage, and leading to instability). This needs to be investigated. Seepage was detected at the toe of the outer wall of the moraine dam. Follow up investigations will be needed to identify the source of the seepage which could be the melting of dead ice or from local drainage. Regular monitoring will also be needed as discharge and debris from side valleys drop into the lake.

Temporary blockage of the lake outlet over the moraines by freezing water and snow barriers, or lake ice debris is very unlikely because the lake outlet has a wide artificial channel through the moraine dam that functions as a spillway. During the field investigation, the team noted that the gated artificial outlet channel was functioning satisfactorily, but they also noted vibrations in the anchor blocks as well as subsidence in the gabion walls. These two features should be monitored regularly.

Monitoring of the hanging glaciers and the likelihood of them breaking off is one of the major practical challenges in the hazard assessment of Petrov's lake. They are clearly visible as they have a limited area. Climatic data should be recorded and monitored regularly in the lake area, particularly extreme climatic events and their impacts.

3.2.6 Stability of the moraine dam.

The elevation of Petrov's Lake is almost 10 m higher than 50 years ago, which is significant in terms of climate regime. The huge water mass seems hanging over the tailings but it is separated by two barriers (Figure. 2). The each barrier is a final-moraine dam. The first of them is lake which was formed for the last thousand years, at late Holocene age. The second lower bank is more ancient. It was formed 15-20 thousand years ago, in upper Pleistocene age. However, the lakeside bank is holding 105 $million\, m^3$ of the Lake Petrov's water from discharge down the valley. It is also supposed that the lower bank would hold the outburst flow in case of the Petrov's Lake outburst and would diverse the water mass of the breached lake from the tailings facilities currently containing 100 $million\, m^3$of wastes with cyanide and continues that if "the outburst flow is significant (**up to several thousands of m³/sec**), its power will be enough for washing out of the second barrier and destruction of tailings dump.

3.2.7 Lake growth.

The physical characteristics of the lake as identified during the field surveys of 2013 are summarized in Table 3.2.

The development of lake began at about the same time through amalgamation of small ponds. The more rapid initial growth of Petrov's lake resulted in it becoming one the largest moraine-dammed lake in Kyrgyzstan. The lake is moraine-dammed and in contact with their associated glacier, and have thus mainly expanded towards their glacier terminus in parallel with glacial retreat and calving. Over the last decade, the expansion of Petrov's Lake has been maximal and the glacier terminus is retreating. Its southern section close to the end moraine is widening.

The volume of lake is increasing by an average of 0.26 million cubic metres per year. The water depth of lake increases toward the glacier termini, but here the lateral moraines are 50-100 m in height and either in contact with bedrock or with debris or talus cover. Thus, the lateral hydrostatic pressure exerted by the greater depths are more or less counterbalanced by the lateral moraines, and the expansion of the lakes has not added any extra lateral pressure to the relatively weak moraine at the outlets.

3.3 Possibility of Petrov's Glacier Lake outburst flood (GLOF).

Intensive development of thermokarst processes, state and structure of the moraine dam is extremely variability, causing the possibility of an outburst of Petrov's Lake. Petrov's Lake breakthrough can occur both surface and underground way. Surface lake breakthrough possible by deepening existing closure channel in the body of the dam through which the Kumtor river flows out of the lake.

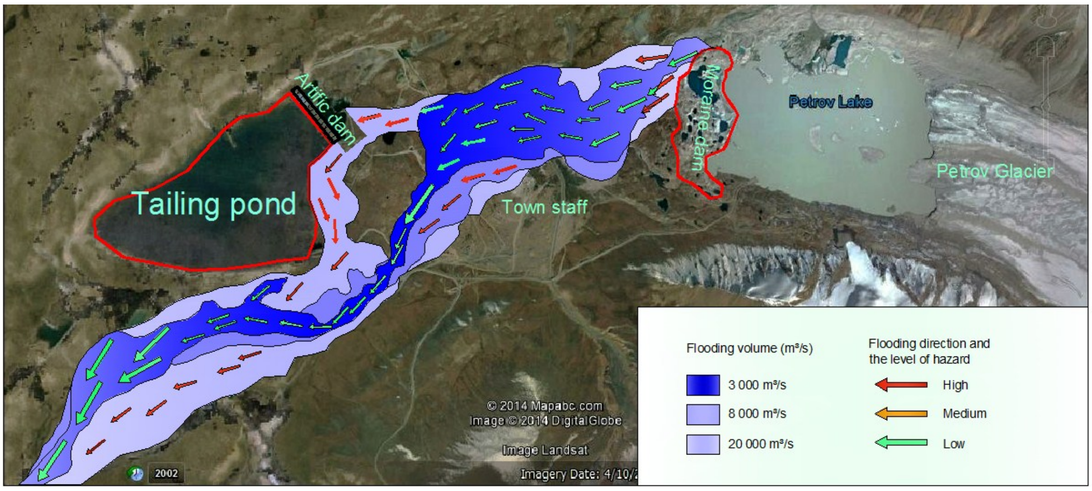


Figure 3.4 Modeling of glacial lake outburst flood at Petrov's Lake.

In 1998, was modeled scenario at the lake surface breakthrough on existing Kumtor riverbed for the case with the maximum flood flow outburst up to 400 m^3/s. Assessment of the affected area, adjacent to the mine lake Petrov's showed outburst flow will be large. It will concentrate along the river Kumtor expanding (up to 260 m) in some areas expanding and narrowing the narrow valley bottom areas. The calculation of flooding showed that a GLOF could threaten the flow of the Kumtor mine tailings.

Tailings pond of "Kumtor" gold mining company. "Kumtor" Tailings Managements Facility (TMF) is a complex of special hydraulic structures and equipment designed to contain wastes from processed mineral resources called tailings. The Tailings Management Facility of the Kumtor mine is located in the Arabel River Valley 6.7 km from the gold mill. TMF contains is crushed rock with chemical admixtures formed as a result of a gold recovery process. Gold recovery at Kumtor averaging 80%, the TMF contains, according to preliminary estimates, approximately 65 tonnes of gold. Thus, with proper technology available, reprocessing of tailings is possible for gold recovery purposes. (Figure 3.5).

The dam is 3,000 meters long and 34 meters high. The dam is of trapezoidal cross-section while the dam crest is 10 meters wide. A 100-meters synthetic antifiltration liner was placed on the upstream side of the dam to prevent erosion, seepage and freezing of dam body.

Local and foreign experts have jointly developed methods and technology of dam buildup, according to which a local design organization in Kyrgyzstan has developed a special dam buildup project. At present, the dam has an elevation of 3,664 meters above sea level. In 2016, the dam will be raised to its final elevation of 3,670.5 meters, thus enabling the TMF to contain 87.7 million cubic meters of tailings.

Figure 3.5 Tailings pond of "Kumtor" gold mining company.

3.3.1 Glacier Lake outburst failure triggers.

Hydrometeorological factors such as air temperature, humidity, radiation, wind speed, wind direction, and precipitation influence glacial melt, discharge into the lakes, and melting of buried ice. The lake has an effective discharge capacity, hence there has been no significant rise in water levels. Undercutting of moraine slopes is not a substantial threat.

Extreme events such as heavy snowfall or very high temperatures could destabilise the lakes. Earthquakes could also affect moraine and lake stability, however assessment of the potential danger of glacial lake outburst as induced by earthquake tremor is most likely beyond current competence.

The erosion areas of the glaciers were covered by debris derived mainly from the slopes above. The Petrov's glacier has several transverse crevasses and collapse features; they are caving into the lakes, although the collapsing masses of ice are not large enough to generate dangerous displacement waves. Also in this case of Petrov's glacier should be monitored for signs of instability as they could potentially produce ice blocks.

3.3.2 Potential GLOF hazards.

Petrov's lake's storage volume of 105 million cubic meters, dam height of 45 m, lowest freeboard, and narrow dam cushion, means there is more likelihood of a GLOF occurrence. The lake needs to be monitored for seepages which can cause moraine dam failure by piping/undermining. Similarly, other key features including hydrometeorological conditions such as lake water level, excessive drainage, or extreme climatic conditions, and dam conditions terminal moraines and moraine dam crest height and width should also be monitored.

There is a further need to assess the influence of the surroundings, for example the impacts of hanging glaciers; debris flows/slides; and the condition of associated glaciers that may generate calving on a scale sufficient to cause a large surge wave. Variation amongst all of these features may influence GLOF hazard levels. Tectonic activity or earthquake induced GLOF hazard is a possibility that should be considered, although prediction is beyond the current competence.

They also talked about possible flood of tailings pond. If the volume of water actually destroys part of the tailings dam, it can be a disaster in the region. Because, contaminated water gets into the largest river in Central Asia. Naryn river basin fully comes to unsuitability. Water pollution affects the soil which 70% of the population uses. Unsuitability of the water affects will regionally.

Overall the findings indicate that the immediate risk of a GLOF occurring is much lower than had been postulated for lake; but many factors cannot be assessed and catastrophic changes cannot be predicted. Thus there is an urgent need for more information as well as for regular monitoring and early warning systems.

3.4 Possible consequences of the Petrov's (GLOF).

The Outburst moraine-glacial lakes - one of the most devastating natural disasters in high mountain areas, because their result can be disruptive floods and mudslides that extend for tens of kilometers down the valleys, destroying infrastructure and taking away human life. As noted above, this is the most dangerous - a outburst of lake, under the moraine channel (tunnel) at the dam of the outburst site, which may be accompanied by the transformation of hydrodynamic outburst wave to stone devastating mudslide. Bathymetric survey calculations show that the maximum volume of the outburst may reach 39-40 million m^3.

Petrov's GLOF events have downstream impacts at four different levels: individual household, village, district, and national. At the household level, impacts are either direct (from inundation) or secondary (e.g., from erosion or landslides). At the village level, people are affected by a loss of natural resources and service infrastructure. At the district level, damage to physical infrastructure disrupts the flow of goods and services, and at national level power supplies are disrupted because of damage to hydroelectricity projects, affecting populations living far beyond the GLOF area.
The moraine dam failure of such a scenario for the Petrov's Lake may result in the following consequences:

3.4.1 Economic consequences.

The impact of a GLOF event downstream is quite extensive in terms of damage to roads, bridges, trekking trials, villages, and agricultural lands as well as the loss of other infrastructures. In the territory of Kumtor valley have a lot of industrial objects. One of main is Kumtor Gold Mine Company.

Kumtor Gold mine company is an open-pit gold mining site in Kyrgyzstan located in the Kumtor valley about 1.5-2 km northwest of the Petrov's glacier lake 350 km (220 mi) southeast of the capital Bishkek and 80 km (50 mi) south of Lake Issyk-Kul. Located in Tian Shan mountains at more than 4,000 m (14,000 ft) above sea level, Kumtor is the second-highest gold mining operation in the world after Yanacocha gold mine in Peru.

The camp of the Kumtor mine complex (main camp, administration and maintenance facilities) is sited in such a vulnerable location (Figure 3.4), downstream of the Petrov's glacier lake that the possible water movement toward the camp will present an essential risk, presenting risks throughout the operating life. Huge financial costs that were invested for infrastructure are threatened. If we assume that the data from the company's website the total amount spent on the creation of the camp is over 50 million dollars.

In addition there is also the risk of flooding civilian objects on the road flooding. As mentioned above, bridges, roads, villages will be under threat of flooding. This will result in a huge financial cost which will affect the country's economy.

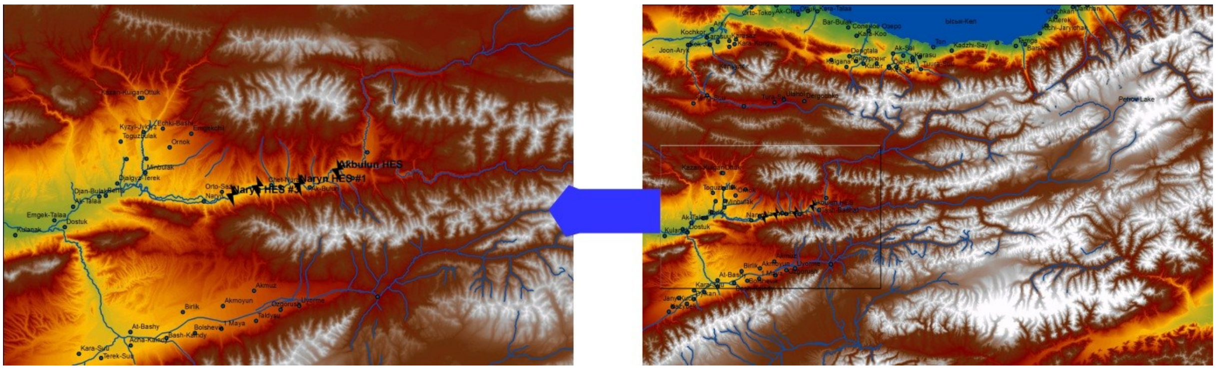


Figure 3.6 Location schemes of hydroelectric stations.

Constructors of hydropower plants on the Naryn River also concerned about the situation on the Petrov’s Lake. Because the shock wave of flood can cause damage to constructions. However, if we bear in mind that Akbulun hydroelectric dam located at a distance of over 150 kilometers from Petrov’s lake, the risk of failure is unlikely (Figure 3.6.).

3.4.2 *Environmental consequences.*

Kumtor gold company inability to prevent the Petrov’s glacier melting into the lake leaves little hope that outburst flows can be controlled. Though Kumtor gold company has been making an extensive effort to address, the problems are likely to continue long time unless and until a mechanism is designed and installed to address them in revised operating plans that remove the tailings from the Lake Petrov’s outflow path or other design sufficient to prevent or eliminate the glacial flow risks that current affect operations.

Should take into account that now the tailings dam is unstable, because it was built on the grounds, which began to melt during the filling bowl tailings. On the basis of geotechnical monitoring since April 1999 has been fixed movement dam to the south-east side. Stabilization of the dam has become a big problem for the company. In 2006, was begin a project to build an extended wedge in the lower slope of the dam. The result has been to reduce the rate of displacement of the dam from 3.6 - 6.6 *mm/month* to 0.9 $mm/month$. Final conclusion about the effectiveness of the decision experts can give after some time, because there are concerns that the rate of displacement of the dam will continue.

In the case of the destruction of the eastern side of the dam by mudflow, this may occur after the Petrov's Lake outburst is not excluded that cyanide-containing waste gets into the river basins of the Kumtor-Naryn. It will be transformation of hydrodynamic outburst of the lake to ecological catastrophe on a regional scale. Likelihood of this scenario increases significantly, because the water level in the lake increases too.

If the waste from the tailings pond gets into the Naryn River, one of the key water sources of Central Asia will become worthless. Will harmed not only to water source, but also all of vegetation and after animal world of the Naryn river basin. Catastrophe can bring huge environmental and economic losses.

3.4.3 Human life loss consequences.

The analysis takes into account the risk of loss of human lives, too. Because the possibility risk of outburst flood the huge volume of water is very high. And it is impossible to guess the events that may carry human life, but still we need to consider the consequences with maximum casualties.

If we will take into account the scenario of a lake outburst flood with the volume >40 million m3 flow outburst wave, then under threat of flooding can be more than several villages, camp of Kumtor gold mine (more than 150), also workers on the power plants. Since the settlements are at a distance of 150 km, the possibility of evacuation great. Under threat are the employees of gold-mining company, who are located at a distance of 1 km from the lake.

The vulnerability of people living downstream from the three lakes differs in relation to the livelihoods and infrastructure characteristics of each area. Overall, the risk may change with passage of time and may also increase in the context of current atmospheric warming. In national terms, other lakes must also be considered. It is essential to develop an appropriate strategy and policy as well as short- and long-term action plans for Petrov's GLOF risk management. The findings of the current study serve as a resource guide and provide materials for assessing GLOF hazards, socioeconomic vulnerability, and GLOF impacts downstream in Kyrgyzstan. It is hoped that the findings will be useful in designing GLOF risk management and reduction strategies in Kyrgyzstan, as well as throughout the Tian Shan region.

3.5 Monitoring, Early Warning and Mitigation.

Risk results from a combination of the actual hazard and the vulnerability of people and their environment. Thus a risk can be minimized by lowering the level of hazard as well as by reducing vulnerability. Mitigation is the word used to describe actions to reduce the hazard and risk level.

Mitigation measures can be structural and non-structural. Measures include monitoring to provide an early indication of changes, early warning systems (EWS) to provide downstream residents and owners of infrastructure time to take avoidance action, and mitigation measures to physically change the situation and reduce the hazard and risk.

Kyrgyzstan hasn't made considerable progress in GLOF risk knowledge, risk assessment, mitigation and early warning. But, several government structures (Ministry of Emergency Situations and Central Asian Institute of Applied GeoScience) holds monitoring of Lake in every year. Structural mitigation activities for GLOF risk reduction weren't carried out for Petrov's Glacier lake, because such measures are very expensive and it is unlikely that this approach could be utilised in the case of all glacial lakes in Kyrgyzstan that have been identified as potentially posing a risk of a GLOF.

3.5.1 Monitoring.

Monitoring GLOF hazard levels requires a multi-staged, interdisciplinary approach using multi-temporal data sets. Key indicators include changes in the lakes and their impoundments which should be observed using different data sets at varying time scales to evaluate glacier hazard and stability of moraine dams. A considerable amount of information can be derived using remote sensing approaches to identify changes in lake size. Monitoring of critical lakes may require direct periodic observation. To be effective, this should be carried out in cooperation with all stakeholders: communities, government departments, institutions, agencies, and broadcasting media, and others.

3.5.2 Early Warning.

At this time, the government is considering a project to provide early warning for dangerous lakes.
Early warning is defined as: "The provision of timely and effective information, through identified institutions, that allows individuals exposed to a hazard to take action to avoid or reduce their risk and prepare for effective response". For an early warning system to be effective, it must integrate four elements: knowledge of the risk, a monitoring and warning service, dissemination and communication, and response capability.

Early warning systems need to be technically sound, simple to operate, easy to maintain or replace, and reliable so that accurate and timely warning can be given. The human communication networks must be capable of relaying the warning to the appropriate authorities. Maximum effectiveness would most likely be achieved if the warning systems are placed in the hands of the local communities.

3.5.3 Mitigation.

There are several possible methods for mitigating the impact of GLOFs. The most important mitigation measure is to reduce the volume of water in the lake, thus reducing the magnitude of the possible peak discharge at the time of breach. Structural mitigation measures can also be applied downstream to protect infrastructure from peak floods.

The volume of water can be reduced by means of one or more of the following: controlled breaching of the moraine dam; construction of an outlet control structure; pumping or siphoning the water from the lake; and tunnelling through the moraine barrier or under an ice dam.

Preventative measures can also be carried out around the lake and also tailings pond to secure against potential threats such as loose rocks or snow/ice avalanches that could trigger displacement waves.

Infrastructure downstream (diversion weirs, intakes, bridges, or river bank settlements) can be protected against a possible surge through proper construction that allows sufficient space for the flow of water and avoids damming. Bridges should have appropriate flow capacities at elevations higher than expected GLOF levels and the spans of piers should not be obstructed by uprooted tree trunks. Land use zoning should also be considered as an effective approach to mitigation by reducing the structures and elements at risk. Among others, settlements should not be built on or near low river terraces within the GLOF hazard zones. River banks with potential or old landslides and scree slopes near settlements should be stabilised and appropriate warning devices installed.

3.5.6 Awareness Raising.

Besides monitoring lakes, it is essential to raise local awareness, and increase knowledge about how to respond. Community and local government bodies should focus on monitoring the lakes, mitigating their vulnerability to GLOF, and preparing to cope with such events should they occur: early warning begins with disaster preparedness. This involves raising awareness about glacial lakes, their characteristics, level of hazards, and the required responses during and after GLOF events.

4. RISK ASSESSMENT.

4.1 Preliminary analysis and scope of the study.

The first problem is the geotechnical issues relating to the Petrov's glacial lake. Also, I have grouped several aspects of impact to gold mine infrastructure. These following aspects:

- Risk of possible failure of the Lake Petrov's natural moraine dam – and resulting Glacial Lake Outburst Flood (GLOF) and its catastrophic impact to tailings pond and contamination of water of Central Asia.

This is an analysis that includes: identification of an initiating event, the factors that determine the initiator to reach potential accident scenarios, the consequences and damage that may occur in the case where the accident sequence is given.

Detailed GLOF hazard and risk assessment is undertaken by simulating GLOF scenarios. Numerical hydrological modeling of the Petrov's glacial lake was carried out using data from the field investigations and from secondary data sources.

For risk assessment used three possible initiators have been considered:

1. Increase in water level in the lake, which leads to the destruction of the moraine dam;
2. The great earthquake that will lead to several possible consequences:
    - Destruction of the moraine dam;
    - The emergence of large water waves on the surface of the lake;
    - Tailings dam destruction (Parallel destruction of the moraine dam and tailings dam is also possible);
3. Erosion or displacement of the moraine dam.

For each initiator was used individual solutions that have enabled the high quality analysis.

4.1.1 Modeling Objective and Approach.

The main objective of GLOF modeling was to simulate moraine dam failure of the high priority lakes and assess potential GLOF impacts downstream. The specific objectives were:

- to develop a glacial lake breach model;
- to develop a model of flood propagation in the valley downstream;

- to forecast flood velocity of flow;
- to assess downstream GLOF impact.

The study was in three stages:

- modelling outbursts;
- modelling flood propagation downstream and flood mapping;
- downstream GLOF impact assessment.

4.1.2 Sources of data.

A *Event tree modelling* by *Reability Workbranch* of approach was applied for GLOF simulation and vulnerability assessment. Topographic information about the study area determines the accuracy and reliability of the model. Topographic information about the study area determines the accuracy and reliability of the model. Spatial data such as a digital elevation model (DEM) of the study area, inline structures of rivers, land use/cover, settlements, infrastructure, and administrative boundaries were derived from the topographic maps of Kyrgyzstan prepared by the Department of Cartography of Kyrgyzstan, and satellite image of SRTM and LANDSAT.

The 2009 field survey provided data about the lakes including the surface area, maximum depth, and top and bottom elevations, and information about moraine dams including the inside/outside slope, dam length and width, unit weight of dam material, porosity, diameter of particles, and internal friction angle.

A digital elevation model (DEM) of the study area was prepared; the Arc GIS modelling package was used to fill sinks and generate rivers for input into cross sections.

The computer applications used for modelling watershed boundaries, river flow, and basin and river properties included ArcGIS/ArcView, was used to acquire geometric data sets from the digital terrain model; and ArcScene/ArcView were used for GLOF modelling.

4.2 Methodology of analysis.

In this section the methodology was carried out to analyze the economic, environmental and human life loss risk in the potential outburst flood area; which covers the steps of identifying accidents, modeling and risk quantification.

There are various methods of identifying potential hazards, monitoring their development and estimating the probable magnitude of such event. Usage of particular methods and their combinations change over time with future bringing new possibilities and technologies. Comprehensive procedures for making assessment of potential glacial hazards have been developed focusing on a certain high-mountain region.

4.2.1 Remote sensing.

Remote sensing proved to be very helpful in identifying potential hazards especially in areas poorly accessible for physical or political reasons. Contactless monitoring of such places in high mountains may be carried out more frequently than terrain research which is often more expensive. There are two types of remote sensing: air-borne and space-borne.

Remote sensing suggests selecting the most appropriate data source depending on the temporal, spectral and spatial characteristics of the observed hazard. Temporal resolution of imagery is the minimum time between two consecutive scanning of the same place on Earth. It relates to the rate at which a certain hazard develops. For example, glacier surges may develop during few days or weeks and therefore require regular and frequent monitoring, whereas formation of a glacial lake takes years or decades so yearly observations are sufficient. For long-term monitored hazards the length of data archive is very important as the tendency and future development may be estimated.

4.2.1.1 Space-borne remote sensing.

Satellite sensors may yield information independently of the political, topographic or financial restrictions. Data of medium resolution cover up to tens of thousands square kilometers by one scene and are becoming well accessible, cheap (few $EURO/km^2$ or much less) and a repeated cycle of few days is often possible. Satellite imagery of high mountain regions began to be archived in 20 the 1980´s so the longest periods of acquisition are almost three decades, which is important in monitoring long-term changes within glacier areas. SRTM (Shuttle Radar Topography Mission) has a long period of acquisition, its spatial resolution of 90 m predestinate it solely for usage in first-order assessments. There are also optical sensors of medium spatial resolution such as Landsat TM (Thematic-Mapper). These have spatial resolution in the range of 28 m which makes them suitable for examination of surface morphology, e.g. glacier lakes, moraine dam.

All of these satellite images with medium resolution are free for using them for noncommercial purposes.

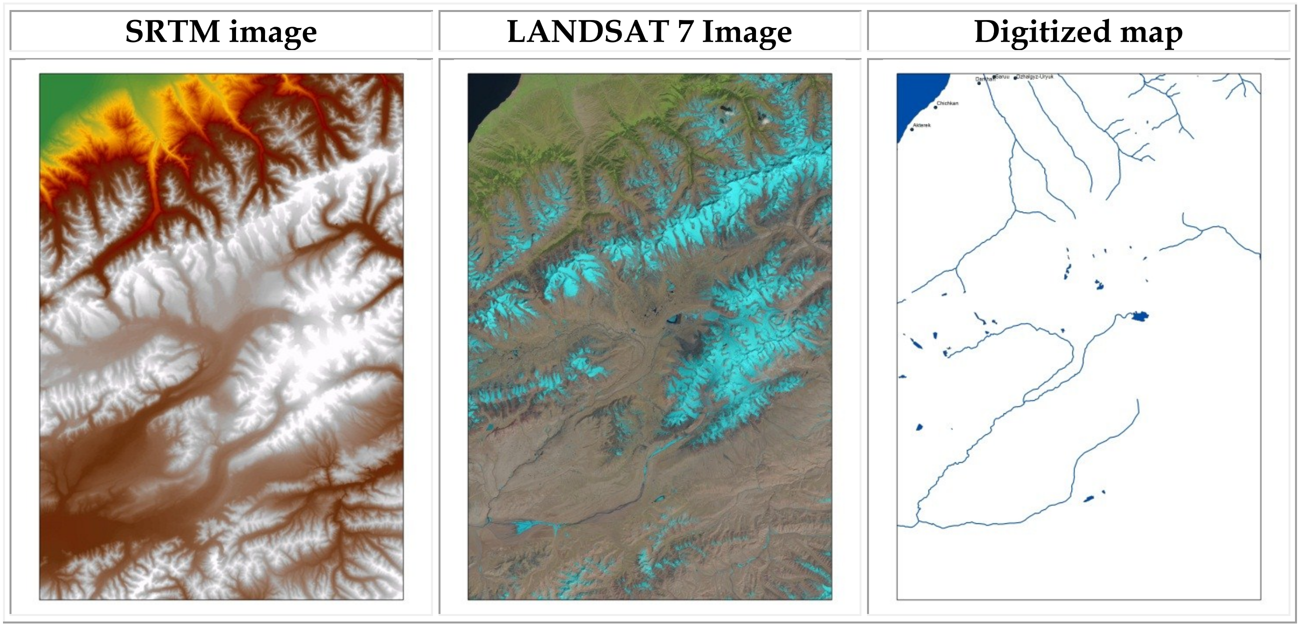


Figure 4.1 Digitizing of map on the Arc GIS software.

4.2.1.2 Air-borne remote sensing.

Aerial photography has longer tradition than space imagery so the archives offer successions convenient for comparison and trend-monitoring of glaciers or lake formation. Spatial resolution is very high but one scene covers usually few or few tens of square kilometers, which is incomparable to satellite sensors. Processing of the photographs allow relatively accurate mapping of high mountain terrain within visible to near infrared (V-NIR) spectral region. But as you know, for the quality you have to pay. Aerial photographs are very expensive for some works. And so it remains to use satellite images.

4.2.1.3 Application on glacial hazard assessment.

Remote sensing is used in glacierized regions for monitoring of horizontal and vertical displacements as they often signify a potential hazard development. Basic parameters used for remote sensing identification of potential hazards are summarized in Table 2.

Risk for breaching of a moraine dam can be evaluated by remote sensing in contrast to glacier outbursts from englacial or subglacial drainage systems. Moraine-dammed lakes are easily detectable, time series are particularly useful for assessing dynamics and estimating of future development. Recognition of moraine dam characteristics (dam geometry, deformation, settlement, surface material) requires high-resolution and high-precision techniques. Monitoring of associated glacier (its geometry, surface type, thickness changes, velocity etc.) is also important as it may help assessing of the glacial lakes evolution.

Glacier surges as well as stable advance or retreat can be tracked by high-frequency remote sensing; mass changes from repeat DEM. Surge-type glaciers can often be recognized from deformed, "looped" moraines. Possible source areas of ice avalanches are searched depending on occurrence of steep glaciers through combination of spectral data with DEM. Also areas of potential debris flows that may accompany glacier floods or lake outbursts can be detected by remote sensing. With sufficient spatial resolution it's possible to estimate the availability of loose debris in a potential flood path and its slope.

Table 4.1 Basic parameters used for remote sensing identification of potential hazards.

	Glacier lake floods	**Debris flows**	**Ice avalanches**
Surface characteristics	lakes on/ at the margins of a glacier expanding lake area steep moraine-dammed lakes	debris accumulations occurring within (recent) glacial zones	steep glacial ice
Critical slope gradient	sediment entrainment and hyperconcentration: 10°	flow initiation: 25-38°	temperate ice: 25° cold ice: 45°
Maximum probable runout.	clear water flood: may exceed 200 km and attain angle of reach < 3° GLOF triggered debris flow: angle of reach 11°	angle of reach 11°	angle of reach 17°

4.2.2 Terrain research.

All of described methods were used during a terrain research of Petrov's Lake and its moraine dam. Hydrological methods include bathymetric measurements realized with the aid of rubber dinghy and an echo-sounder with the accuracy for depths up to 50 m ranging from 10 to 30 cm (Figure 3.3). These measurements were systematically carried out on the lake and served to determination of the changes in depth and volume which have taken place during the past few years.

Next, physical and chemical parameters of lake water quality (temperature, dissolved oxygen, oxygen saturation, conductivity, salinity or pH) were measured down the vertical profiles. Hydrological measurements of all inflows and outflows should be done to calculate the lake water balance and fluctuations of water level.

Climatic data, especially temperature and precipitation trends during the year, is also very important to monitor as the highest temperatures (and therefore ice/ snow melting) often occur together with increased rainfall which may raise lake water level and trigger its outburst (Figure 3.1). Meteorological stations installed in high mountain areas are often automated and send data in regular intervals directly to the researchers.

Geophysical methods include exploration of a dam structure, especially near the lake outflow as erosional processes may threaten the dam stability. Changes in morphology of the moraine dam should be monitored and compared with last investigation. If a glacier terminus is close to the lake, a survey of its margin is necessary, together with examination of crevasses and a rate of calving. Areas of subsidence are often closely monitored as they may be resulting from thermokarst processes and the dam may be destabilized.

An accurate demarcation of a lake shoreline and glacier snout can be carried out either with total geodetic station or with GPS measurements.

4.2.3 Procedures of hazard assessment.

Different procedures of hazard assessment are applied for different high mountain areas around the world as the local conditions may vary significantly. Assessment procedures are mostly based on gained experience and historical cases within a certain region. The next chapter presented one of methodology for first-order assessment of glacial lake outburst hazard, which was compiled by R. J. McKillop and J. J. Clague and it concentrates on moraine-dammed lakes.

After identifying the possible lake outburst, each scenario is evaluated in detail. Triggering event is a physical fact that has specific causes analysis and can generate an incident or accident, depending on the evolution in space-time. Having a list of initial events, we continued to identify the parts of the system for each case. This table is called "Failure Modes and Effect Analysis".

4.2.3.1 Identification of accidents/initiators.

Nowadays, most of organizations are interested to design and develop contingency plans for GLOF scenarios. State organizations are among most critical ones to make reasonable decisions about develop such plans that identify most probable risks, their modes and effects as well as determine appropriate techniques and models as tools for assessing GLOF risks and prioritize them and design and develop practical and rigor contingency plans to response better during disasters and aftermath. One of most important techniques as "Failure Modes and Effects Analysis" (FMEA) and special version of it for organizations "Failure Modes and Effects Analysis" (FMEA) tries to help managers and planners of this sector to be good practitioners in this field.

"Failure Modes and Effects Analysis" (FMEA) is an inductive analytical method which may be performed at either the functional or piece-part level. "Failure Modes and Effects Critically Analysis" (FMECA) extends (FMEA) by including a criticality analysis, which is used to chart the probability of failure modes against the severity of their consequences. The result highlights failure modes with relatively high probability and severity of consequences, allowing remedial effort to be directed where it will produce the greatest value: FMECA=FMEA+C

The basic steps for performing a Failure Mode and Effects Analysis (FMEA) include:

- Familiarization with the system, their equipment and functions;
- Selection of equipment and their function;
- Identification of failure modes applicable for the function;
- Study of the effect of each failure;
- Study of the causes of failure;
- Study of existing measures to control the fault and compensation measures;

Results from the Systems FMEA are documented in an FMEA Table that includes the following information.

- **Equipment/Function**: It is the system where characterized with failure probability.
- **Failure mode**: The specific manner or way by which a failure occurs in terms of failure of the item (being a part or (sub) system) function under investigation; it may generally describe the way the failure occurs. It shall at least clearly describe a (end) failure state of the item (or function in case of a Functional FMEA) under consideration. It is the result of the failure mechanism (cause of the failure mode).
- **Failure effect**: Immediate consequences of a failure on operation, function or functionality, or status of some item.
- **Failure cause and/or mechanism:** Defects in requirements, design, process, quality control, handling or part applications, which are the underlying cause or sequence of causes that initiate a process (mechanism) that leads to a failure mode over a certain time. A failure mode may have more causes.
- **Detection or Current Process Controls**: The means of detection of the failure mode by maintainer, operator or built in detection system, including estimated dormancy period (if applicable).
- **Compensatory measure**: It is form of policy, method and mechanism which used when the accident occur.
- **Remarks / mitigation / actions**: Additional info, including the proposed mitigation or actions used to lower a risk or justify a risk level or scenario.

A schematic of the FMEA Table format used, with an example for one failure scenario, is presented in Table 4.2 below.

Table 4.2 FMEA Table Format

Function	**Failure Mode**	**Potential Effects of Failure**	**Failure Mechanisms**	**Current Process Controls**	**Compensatory measure**	**Recommended Action(s)**
Glacial lake						
Glaciers	Melting glaciers. Rising water levels.	Glacial Lake, Moraine dam, Possibility effect to tailings pond, Ground, Vegetation cover,	The rapid melting of glaciers, will raise the water level in the lake.	Geotechnical control, Topographic control of moraine dam, topographic grid, deformation and ground movement.	Find an alternative approach to artificial water removal.	Artificial lowering of the water on the lake. Construction of drainage system. Premature slow destruction of the moraine dam.

As shown, the above table documents a description of the failure scenario including existing safeguards, an estimate of the residual risk for all relevant categories, and any further comments or background on uncertainty associated with the assessment. Where appropriate, a follow up risk rating classification was completed after mitigating measures were assessed. Uncertainty in the assessment (or risk rating) as a result of knowledge base, random process, etc,.

4.2.3.2 Modeling of accidental scenarios.

One of the advantages of using an FSA approach is the ability to clearly illustrate the sequence of events that can take place or are required to take place for a failure to occur. This method effectively illustrates how resistant a system is to single or multiple initiating events. Figure 4.1 displays an example of the layout of an initiating **event fault tree (ET).**

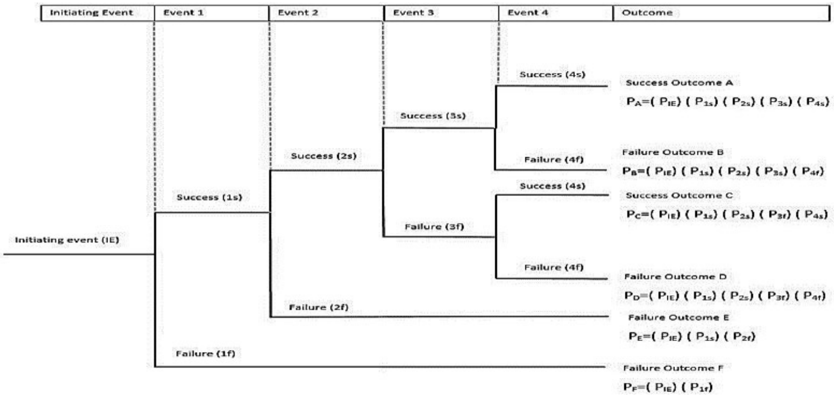


Figure 4.2 Event tree diagram example.

Event tree analysis (ETA) is a forward, bottom up, logical modeling technique for both success and failure that explores responses through a single initiating event and lays a path for assessing probabilities of the outcomes and overall system analysis. This analysis technique is used to analyze the effects of functioning or failed systems given that an event has occurred. This Technique may be applied to a system early in the design process to identify potential issues that may arise rather than correcting the issues after they occur. With this forward logic process use of ETA as a tool in risk assessment can help to prevent negative outcomes from occurring by providing a risk assessor with the probability of occurrence.

The tree is constructed as follows:

- **Initiating event (IE)**: Failure or undesired event that initiates the start of an accident sequence. The IE may result in a mishap, depending upon successful operation of the hazard countermeasure methods designed into the system.
- **Pivotal events**: Intermediary events between the IE and the final mishap. These are the failure/success events of the design safety methods established to prevent the IE from resulting in a mishap. If a pivotal event works successfully, it stops the accident scenario and is referred to as a mitigating event. If a pivotal event fails to work, then the accident scenario is allowed to progress and is referred to as an aggravating event;
- **Outcomes**: Series of events that ultimately result in an accident. The sequence of events begins with an initiating event and is (usually) followed by one or more pivotal events that lead to the undesired end state.

4.2.4 Risk Quantification.

Risk quantification is the process of evaluating the risks that have been identified and developing the data that will be needed for making decisions as to what should be done about them. Risk management is done from very early in the project until the very end. For this reason qualitative analysis should be used at some points in the project, and quantitative techniques should be used at other times.

The procedure used to estimate both components and therefore the risk to the natural environment, described in the following sections.

4.2.1.1 Estimation of Probability.

Probability – A risk is an event that "may" occur. The probability of it occurring can range anywhere from just above 0 to just below 100 percent. During the risk analysis the potential likelihood that a given risk will occur is assessed, and an appropriate risk probability is selected from the table below:

- For the scenario of increasing water volume with rapid melting of glaciers.

Table 4.3 Indicators of probability degree for glacier lake outburst after the increasing of water in a lake.

Probability Category	**Probability (%)**	**Valuation**	**Description**
Very High	25-100	5	Risk event expected to occur
High	19-24	4	Risk event more likely than not to occur
Medium	13-18	3	Risk event may or may not occur
Low	7-12	2	Risk event less likely than not to occur
Very Low	0-6	1	Risk event not expected to occur

(Note: It can’t be exactly 100 percent, because then it would be a certainty, not a risk. And it can’t be exactly 0 percent, or it wouldn’t be a risk.)

- For the scenario of earthquake.

Table 4.4 Indicators for deriving probability of occurrence for glacier lake outbursts after the earthquake.

Probability Category	Probability	Valuation	Description
Very High	🟥	4	Risk event expected to occur
High	🟨	3	Risk event more likely than not to occur
Medium	🟦	2	Risk event may or may not occur
Low	⬜	1	Risk event less likely than not to occur

(Note: Table created from seismic maps of Kyrgyzstan. It was developed by Institute of Seismology (Science Academy of Kyrgyz Republic)).

- For the scenario of erosion.

Table 4.5 Indicators for deriving probability of occurrence for glacier lake outburst after the erosion.

Probability Category	**Range of Hydraulic shear stress τ (Pa)**	**Valuation**	**The rate of increase of the crack.**
High	>100	4	Very Rapid
Medium	51-100	3	Moderately rapid

Low	21-50	2	Slow
Very Low	1-20	1	Very Slow

Probabilities of glacial hazards are difficult to quantify due to the small number of recorded events and limited statistical data set on the flood triggers. The above approaches rely on a detailed data set and are therefore most suited to study of known problem sites. For more information on how to determine if the risk is written in the next chapter.

4.2.1.2 Estimation of consequence.

Below are listed the criteria for the estimation of consequences of each scenario on the glacier lake outburst flood.

Table 4.6 Scales of estimation of consequences.

Quantity	Hazard	Extension	Range
Very High	Very High	Very Extensive	4
High	High	Extensive	3
Medium	Medium	Low Extensive	2
Low	Low	Not Extensive	1

Quality of the environment	Affected population	Assets and production capital	Range
Very High	>100	Very High	4
High	25-100	High	3
Medium	5-25	Medium	2
Low	1-5	Low	1

where: Quantity - quantity of substance released into the environment. (ranging from 4 = very high to 1 = low);

Hazard - intrinsic hazard of the substance; harmful, toxic, cumulative, etc. (ranging from 4 = very high to 1 = low);

Extent - environmental area affected or persons affected by the impact. (ranging from 4 = very extensive to 1 = not extensive);

Quality of the environment - (ranging from 4 = high, space protected to any degree and 1 = low quality);

Affected population – (more than 100 persons - 4, between 25 and 100 - 3, between 5 and 25 - 2 and fewer - 1)

Assets and production capital - (ranging from 4 = very high to 1 = low).

4.2.1.3 Estimation of damage.

The estimate of the consequences is performed differently for the natural, human and socio-economic environment. We estimate the consequences or injury that each scenario produces in the environment, applying the following formulas:

- Damages of natural environment (NE):

$$Damages\ on\ the\ NE = quantity + 2\times hazard + extent + quality\ of\ the\ environment$$

- Socioeconomic damages (SE):

$$Damages\ of\ SE = quantity + 2\times hazard + extent + assets\ and\ production\ capital$$

- Human life loss damages (HL):

$$Damages\ of\ HL = quantity + 2\times hazard + extent + affected\ population$$

Severity estimation of the consequences will be made according to the following scales:

Table 4.7 Scales of severity estimation.

	Evaluation	**Value**
Critical	60-52	5
Grave	51-43	4
Moderate	42-31	3
Light	30-22	2
Negligible	21-15	1

4.2.1.4 Estimation of Risk

Any evaluation has a subjective component associated factors: uncertainty of scientific knowledge, access to sufficient sources of information, existence of different and sometimes contradictory perceptions of the risks and severity, etc.; therefore, the risk assessment must adequately document the judgments and sources of information used.

In any case, the risk assessment will be performed for each postulated accident scenario, from the evaluation of the damage associated with the result or effect for each environment and the frequency of occurrence of those consequences. Damage and frequency correspond to the two components of risk, which allow its estimation using the product of both referred to the type of result.

Once the frequencies or probabilities of the different scenarios and possible consequences on the three possible environments have been determined, the risk estimate is made.

For each scenario the probability (between 1 and 5) is multiplied by the severity of the consequences (between 1 and 5) obtaining a value between 1 and 25, 25; being the highest risk. This is for each of the analyzed environments. This gives three risk estimate values (one for each environment) and an overall value (the sum of these), giving the total risk for each scenario.

$$\boldsymbol{Risk = Probability \times Severity}$$

Where: The consequence is valued based on the natural, human and socio-economic environment.

$$\boldsymbol{Severity = Damages\ on\ the\ NE + Damages\ of\ SE + Damages\ of\ HL}$$

Finally, three tables have been drawn up (one for each environment) indicating on their axes the probability or frequency of a scenario occurring and its gravity (both values range from 1 to 5). In these tables, all the possible scenarios detected including their risk evaluation are specified for each environment.

Table 4.8 Scale of risk evaluation.

Risk evaluation		
Very high risk	21-25	🟥
High risk	16-20	🟥
Medium risk	11-15	🟧
Moderate risk	6-10	🟧
Low risk	1-5	🟨

Scenarios in the table give an indication to assess risk and to suggest improvements in the management of risk reduction.

Table 4.9 Risk analyzing table.

Probability/Severity	1	2	3	4	5
1	Low	Low	Low	Moderate	Medium
2	Low	Low	Moderate	Medium	High
3	Low	Moderate	Medium	High	Very High
4	Moderate	Medium	High	Very High	Very High
5	Medium	High	Very High	Very High	Very High

Risks categorized on a scale, with the code, which includes guidance purpose only and as an example.

5. RISK ANALYSIS OF PETROV’S GLACIER LAKE OUTBURST FLOOD

5.1 Identification of hazards.

Failure of Petrov’s glacial lake dam can cause outburst flood and represent a serious hazard. The potential danger of outburst floods depends on various factors like the increasing of water volume, earthquake, erosion and morphometry of the glacier and its surrounding moraines and valley.

In addition, a potential lake outburst is one of the causes of environmental disaster. The destruction of the tailings, which is located in the valley completely contaminate the largest river of the country.

Petrov’s Glacial lake outburst flood is a biggest natural hazard in Kyrgyzstan. But it also has an industrial hazard such as tailing dam failure. This makes it difficult a risk analyzing. If in the first case it is necessary to determine the properties and identify potential sources of the accident, so in the second case, we determine the risk of impact to the environment. Also necessary to consider that possible sources of dangerous activities, processes, elements of the environment which can compromise the installation, organization, management of human resources and materials, and others.

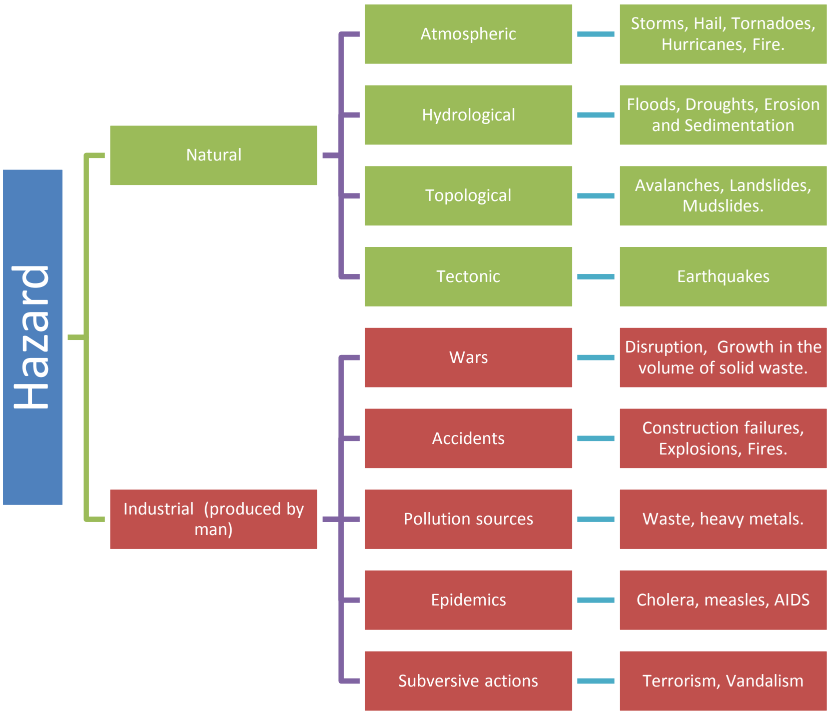


Figure 5.1 Classification of hazards by origin.

5.1.1 Sources of hazards.

Most of the information used in natural hazard assessments is generated by two steps: national and regional natural phenomena research and monitoring centers; disaster management entities; and sectoral planning agencies, ministries, and public utilities.

Sources of Petrov’s GOLF hazard are hazards of regional or national levels. Examples of potential sources are listed in Table 5.1.

Table 5.1 Sources of hazard and its potential damages on the Petrov GLOF.

Sources of hazard	Potential damage
Rising water levels (ice melting, heavy rains)	The problem of the stability of the moraine dam that could lead to flooding.
Earthquakes	The problem of the stability of the moraine dam that could lead to flooding. Also subsequent flooding of the tailings, settlements, water and soil pollution.
Erosion (lateral water erosion)	Destabilization of moraine dam which leads to flooding. Also it can go by earthquake scenario.
Deterioration of the membrane at the bottom of the tailings. Formation of pores and cracks on the membrane. (after glacier lake flooding)	Contamination of the soil and groundwater.

Petrov’s Glacier Lake is a basic threat of the Kumtor mine tailings. All of the factors described in 2 Charter raise concerns that the natural glacial moraine dam impounding Petrov’s Lake and the tailings dam below are both structurally unstable and could fail if a significant earthquake or erosion occurs. Many researchers of Kyrgyzstan prove that these conditions are extremely risky and could result in a catastrophic collapse of the Petrov’s Lake dam, which can also damage the Kumtor tailings pond. This can cause a rapid release of masses of contaminated water and soil (the tailings) into the Kumtor River, endangering downstream people, constructions, rivers, and would likely kill much of the mountain trout population and other aquatic organisms. Such a collapse could negatively-impact waters throughout much of the Naryn River basin.

5.1.2.1 Rising water levels (ice melting, heavy rains).

Depending on the rise of temperature and the melting of glaciers, the first moraine dam break scenario increases the potential impact on the tailings pond. The water level in the lake is increasing every year, and thereby increasing the risk of destruction of the tailings. If in 1957 the possibility flow of breakthrough wave was 168030,2793 m^3/s, but now it is 2960118,715 m^3/s (see Table 3.2 and Figure 3.4). In the following figures showed the possible reasons of scenario.

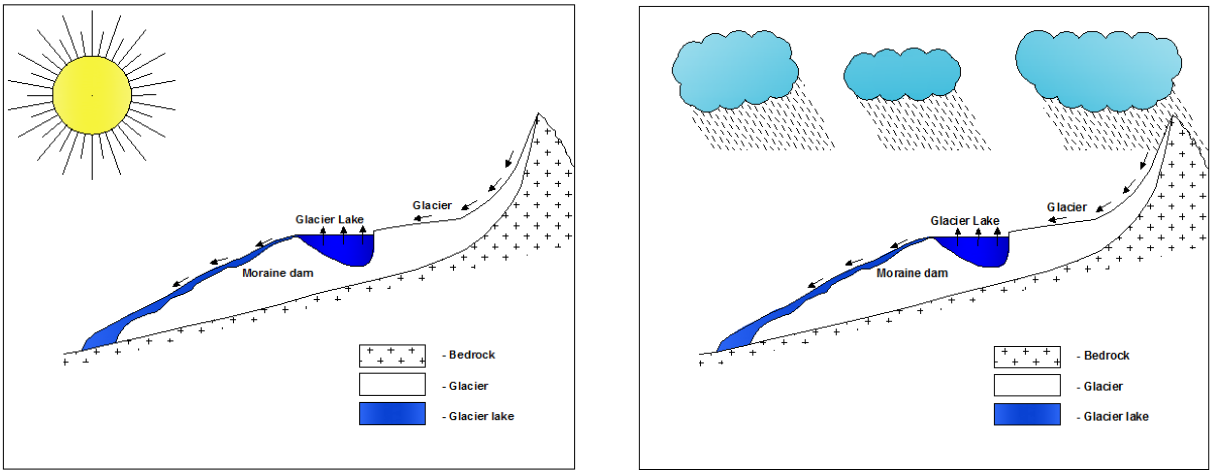


Figure 5.2 Glacier lake outburst flood: a) by high temperature and glacier melting, b) by heavy rains.

5.1.1.2 Earthquake.

It should be noted that the seismic hazard can go both sequentially and in parallel. Because the earthquake can affect to moraine dam and tailings dam at the same time.
The hazard of erosion can also go to a different sequence. First, can the collapse of the tailings and then getting into the river. Despite the options of event the loss or damage of the environment remains large.

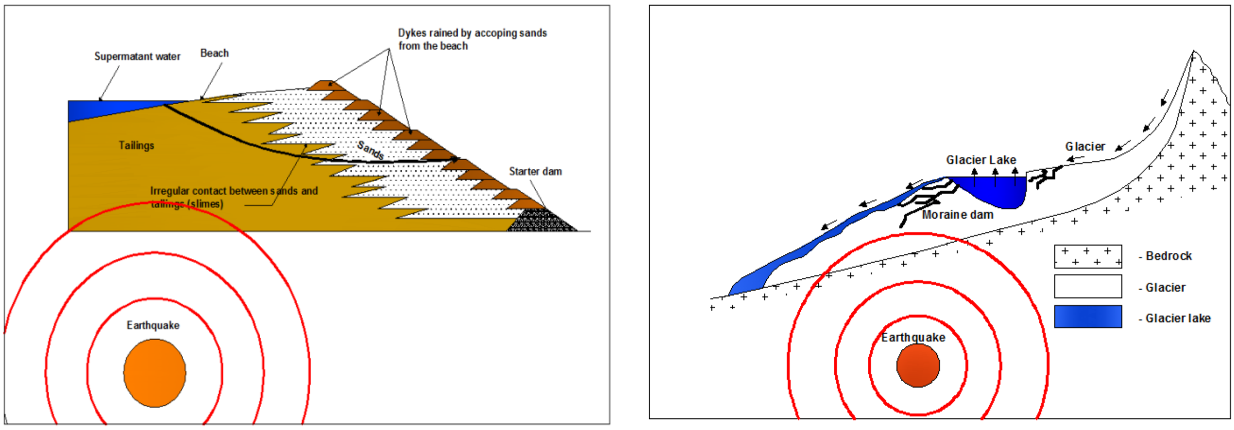


Figure 5.3 Glacier lake outburst flood: a) impact of the earthquake to the tailings pond. b) impact of the earthquake to the glacier lake.

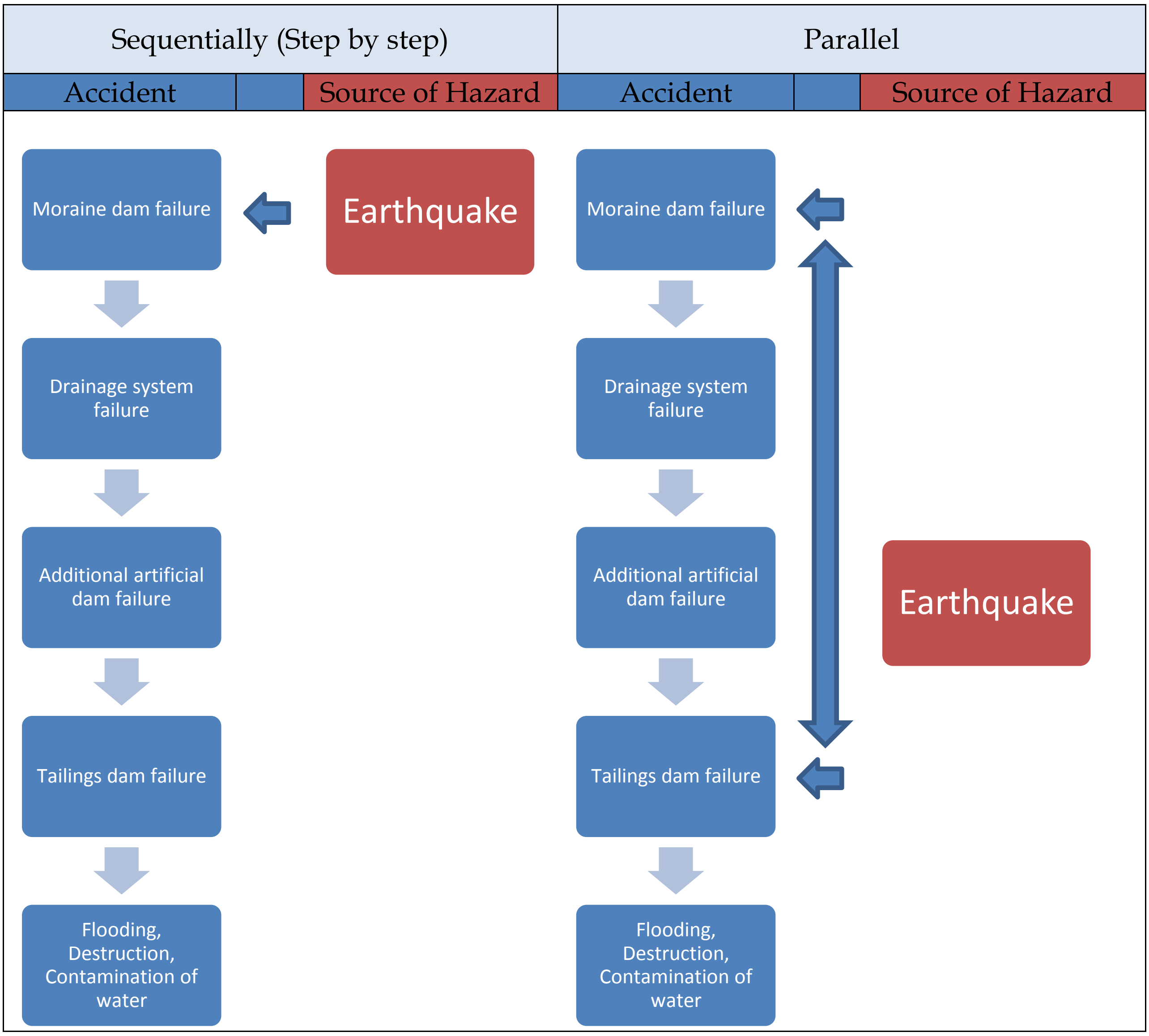


Figure 5.4 Possible scenarios on the Petrov's lake in the earthquake.

The state of moraine dam is the critical factor of the potential outburst in the case of Petrov's Lake. However, the assessment procedure is of a preliminary nature because the precise conditions of potential outburst are unknown.

5.1.1.3 Erosion.

Glacier erosion can lead to a breakthrough lake. Most of the moraine dam is under water. Underwater movements can slowly reduce the thickness of the dam. The study of the underwater part of the lake is very expensive and difficult. Therefore, monitoring of the underwater part of the lake is conducted only once every two years.

Also Petrov’s glacier has several transverse crevasses and collapse features; they are calving into the lakes, although the collapsing masses of ice are not large enough to generate dangerous displacement waves. But in this case of Petrov glacier should be monitored for signs of instability as they could potentially produce ice blocks.

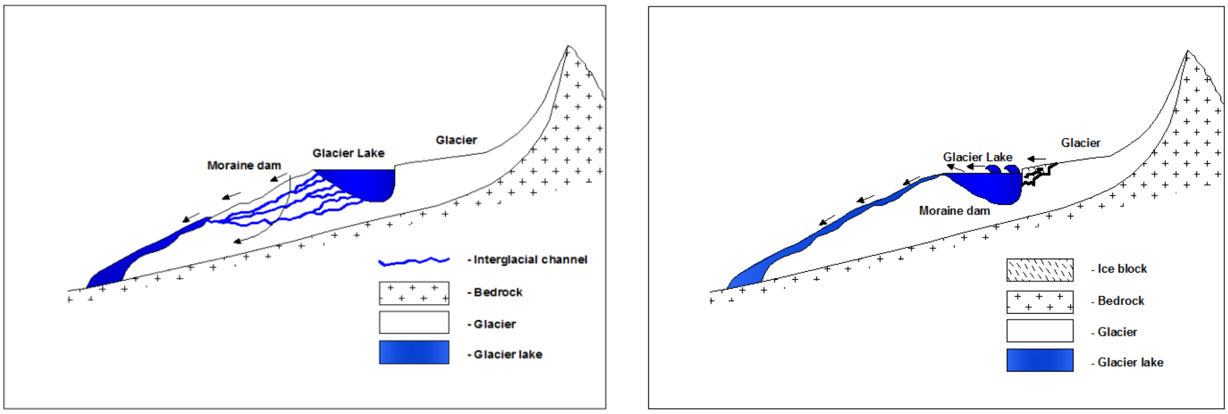


Figure 5.5 Glacier lake outburst flood: a) by erosion in interglacial channel. b) by erosion on the glacier tongue.

5.1.1.4 Tailings pond failure after the GLOF.

Kumtor tailings pond built to contain waste from gold mining, it is the largest tailings pond in the Kyrgyzstan. The construction and care of a tailings dam is a main task to society and people which engaged in mining. Every year on the territory of tailings pond carried different monitorings. The results from the last monitoring of the Kumtor tailings pond were discussed a main risks and methods of their solutions. At this time it has a several problems of safety. These are following risks:

- Threat of glacial lake outburst, which may flood part of the tailings.
- Hydrological factor is one of the most common causes of failure. The majority of failures are due to slope instability, seepage and erosion; all caused by a lack of control of the water balance.
- Large earthquake risk might cause catastrophic failure of a tailings dam, with the release of a large amount of tailings, and could lead to long term environmental damage with huge cleanup costs.

As mentioned above earthquake risk can be realized at the same time with Glacier lake destruction (Figure 5.4). It case can lead huge environmental damage and economic expenditure.

Even if the tailings dam will not be destroyed, the water that falls on the surface of the tailings may cause the risk of erosion. Water can seep in and destroy a dam (Figure 5.6).

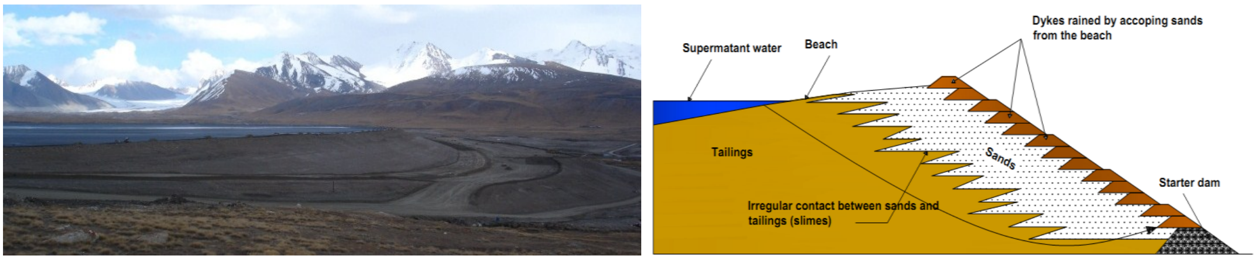


Figure 5.6 Tailings pong of Kumtor Gold Mine Company: a) panoramic photo; b) structure.

And finally, there are two ways to contamination: a catastrophic failure, such as breach of the tailings dam, or a chronic low-level release, such as seepage over an extended period.

Of all environmental risks posed by tailing ponds the most grave is a dam failure. The most critical element of any tailings impoundment is a dam. Stability of the tailings impoundments depends a number of factors: its design, location, presence of the geological and meteorological hazards in the region, etc. As a rule, major source of risk represents dams of older design.

Tailings pond dams can fail because a number of natural hazards as well as natural hazards in combination with anthropogenic factors. Figure 5.7 represents non exhaustive variety of tailings impoundment failure reasons for Kyrgyzstan.

One of the most common reasons of dam failures is pond overtopping due to improper water discharge. In the mountain environment this problem may be also caused by Petrov's lake outburst flood. Secondly, mining wastes sites can be destroyed by landslides which are very frequent in some mountainous areas. Thirdly, an earthquake can certainly be a reason for a dam failure. The destruction of the dam may take place because of direct severe earthquake's shock or as a result of the chain of events:

$$\begin{gathered}\textit{earthquake or ice erosion or rising of water on the lake} \rightarrow \textit{landslide} \rightarrow \\ \textit{dammed lake} \rightarrow \textit{wash} - \textit{off of mining wastes site} \rightarrow \textit{dam break} \rightarrow \\ \textit{dispersion of toxic or radioactive wastes with mudflows}.\end{gathered}$$

$$\begin{gathered}\textit{earthquake or ice erosion or rising of water on the lake} \rightarrow \textit{landslide} \rightarrow \\ \textit{dammed lake} \rightarrow \textit{wash} - \textit{off of mining wastes site} \rightarrow \\ \textit{destruction of geomembrane} \rightarrow \\ \textit{seepage of toxic or radioactive wastes to soil or groundwater}.\end{gathered}$$

Tailings slurry liquefaction as a result of repeated seismic shocks makes threat from earthquakes quite realistic.

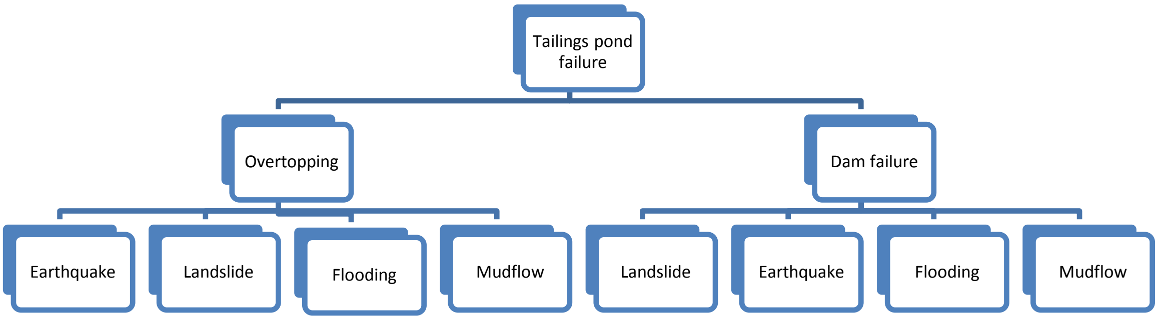


Figure 5.7 Simplified tailings impoundment fault tree: example of Kyrgyzstan.

Therefore, such a diversity of factors which can cause destruction of a tailings pond located in the mountainous environment, rapidly at which released tailings can be transported downstream and their high chemical availability determine that high level of risk associated with mining wastes in Kyrgyzstan.

5.1.2 Risk Evaluation.

Risk evaluations were completed following the identification of risk scenarios and measurement of consequences. The evaluation of risk requires determining the acceptability of risk as defined through the different locations (or risk values) within the risk matrix developed for the risk assessment.

Table 5.2 FMEAC for Petrov's glaciar lake, failure modes, effects and methods of control and compensation.

Function	Failure Mode	Potential Effects of Failure	Failure Mechanisms	Current Process Controls	Compensatory measure	Recommended Action(s)
Petrov's glaciar lake						
Glaciers	Melting glaciers. Rising water levels.	Glacial Lake, Moraine dam, Possibility effect to tailings pond, Ground, Vegetation cover,	The rapid melting of Petrov's glacier, will raise the water level in the lake.	Geotechnical control, Topographic control of moraine dam, topographic grid, deformation and ground movement.	Find an alternative approach to artificial water removal.	Artificial lowering of the water on the lake. Construction of drainage system. Premature slow destruction of the moraine dam.
Glacial Lake,	Earthquake	Moraine dam, Possibility effect to tailings pond, Ground, Vegetation cover,	Collapse of an ice dam. Water wave pressure,	Geotechnical control, Topographic control of moraine dam, topographic grid, deformation and ground movement. Be informed with the closest seismological station.	Frequently perform geotechnical, topographical monitoring, checking the stability of the dam.	Artificial lowering of the water on the lake. Construction of drainage system. Premature slow destruction of the moraine dam.
Glacial Lake	Lateral water erosion.	Moraine dam	Water effects on the lower part of the moraine dam. Formacion of grietas, carcavas.	Using the geotechnical monitoring (stability analysis of moraine dam), which determine displacement of dam.	Depending on the seriousness of the need to strengthen damaged areas.	Artificial lowering of the water on the lake. Construction of drainage system. Premature slow destruction of the moraine dam.

Table 5.3 FMEA for "Kumtor" tailings pond, failure modes, effects and methods of control and compensation.

Function	**Failure Mode**	**Potential Effects of Failure**	**Failure Mechanisms**	**Current Process Controls**	**Compensatory measure**	**Recommended Action(s)**
"Kumtor" Tailings pond						
Tailing dam	Glacial Lake Outburst Flow,	Contamination of ground water, surface water, soil, air, vegetation cover.	Possibility tailings dam failure after the Petrov's Lake flooding.	Using the geotechnical monitoring (stability analysis of moraine and also tailing dam), which determine displacement of dam.	Depending on the severity of the collapse of the dam, it is necessary to strengthen it. At the same time prevent large contamination.	Premature to strengthen the dam. Continuous quality control dam. Geotechnical and other monitoring's.
Tailings pond	Deterioration of the membrane at the bottom of the tailings. Formation of pores and cracks on the geomembrane.	Effect to ground water, soil.	The membranes have a useful life of 20 to 30 years according to the material and the external conditions so that if after this time will not be replaced, pores, tears or other problems that would cause an outflow of liquid may appear.	Monitoring the state of the membrane, and internal conditions that affect and monitor their age.	Replacing of membrane	Replacing of membrane

5.1.3 Modeling Scenarios.

For modeling risk scenarios was used the Reliability Workbench 11.0 software which served for the construction of several event tree (ET).

Event tree analysis (ETA) is an analysis technique for identifying and evaluating the sequence of events in a potential accident scenario following the occurrence of an initiating event. ETA utilizes a visual logic tree structure known as an event tree (ET). The objective of ETA is to determine whether the initiating event will develop into a serious mishap or if the event is sufficiently controlled by the safety systems and procedures implemented in the system design. An ETA can result in many different possible outcomes from a single initiating event, and it provides the capability to obtain a probability for each outcome.

The ETA is a very powerful tool for identifying and evaluating all of the system consequence paths that are possible after an initiating event occurs. The ETA model will show the probability of the system design resulting in a safe operation path, a degraded operation path, and an unsafe operation path.

The purpose of ETA is to evaluate all of the possible outcomes that can result from an initiating event. Generally, there are many different outcomes possible from an initiating event, depending upon whether design safety systems work properly or malfunction when needed. ETA provides a probabilistic risk assessment (PRA) of the risk associated with each potential outcome.

The following are advantages of the ETA technique:

- Structured, rigorous, and methodical approach.
- A large portion of the work can be computerized.
- Can be effectively performed on varying levels of design detail.
- Visual model displaying cause/effect relationships.
- Relatively easy to learn, do, and follow.
- Models complex system relationships in an understandable manner.
- Follows fault paths across system boundaries.
- Combines hardware, software, environment, and human interaction.
- Permits probability assessment.

The following are disadvantages of the ETA technique:

- An ETA can only have one initiating event; therefore multiple ETAs will be required to evaluate the consequence of multiple initiating events.
- ETA can overlook subtle system dependencies when modeling the events.
- Partial successes/failures are not distinguishable.

Petrov’s glacier lake

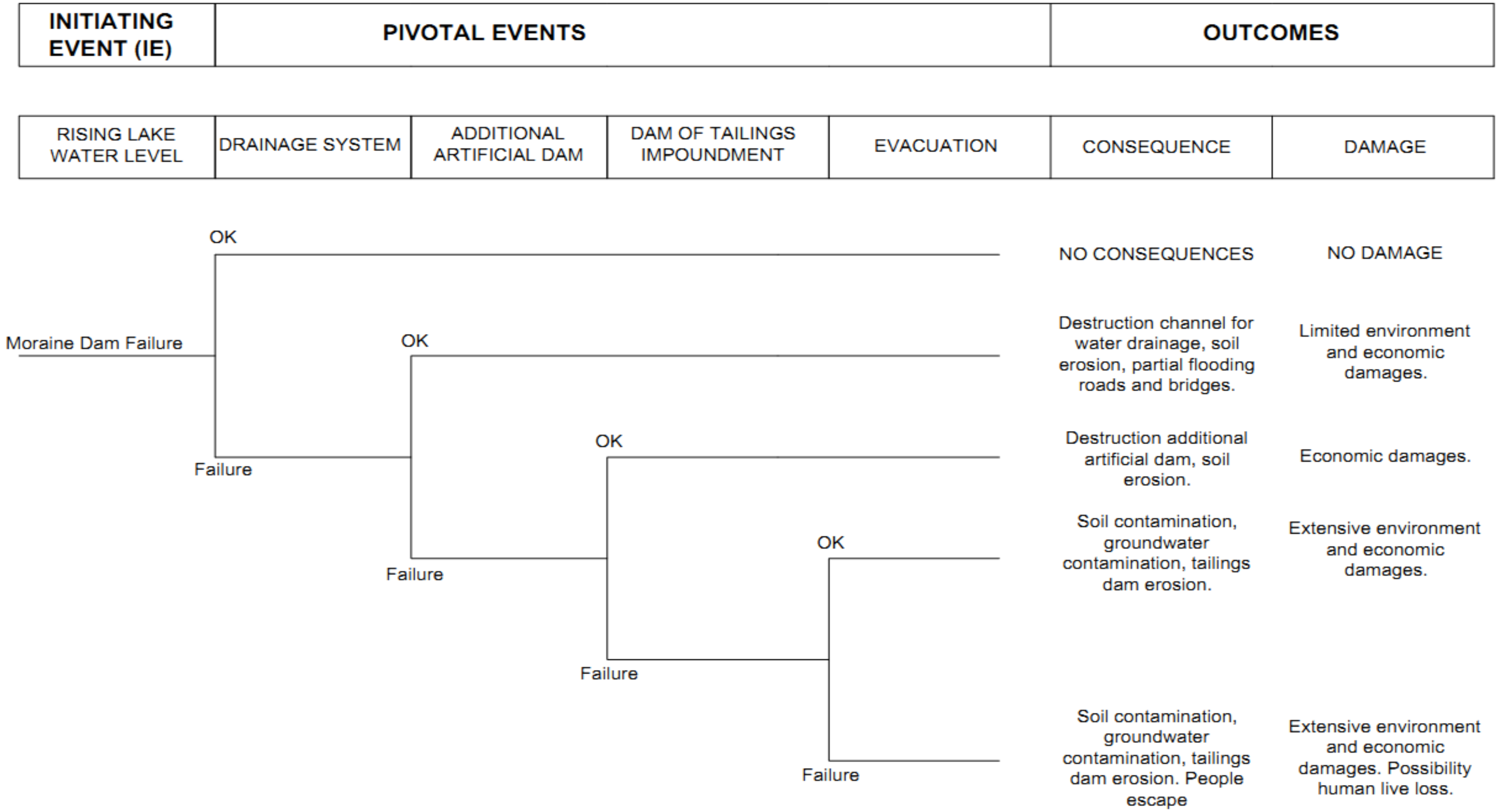


Figure 5.8 Event Tree for Petrov's GLOF consequences associated with increasing of water on the lake.

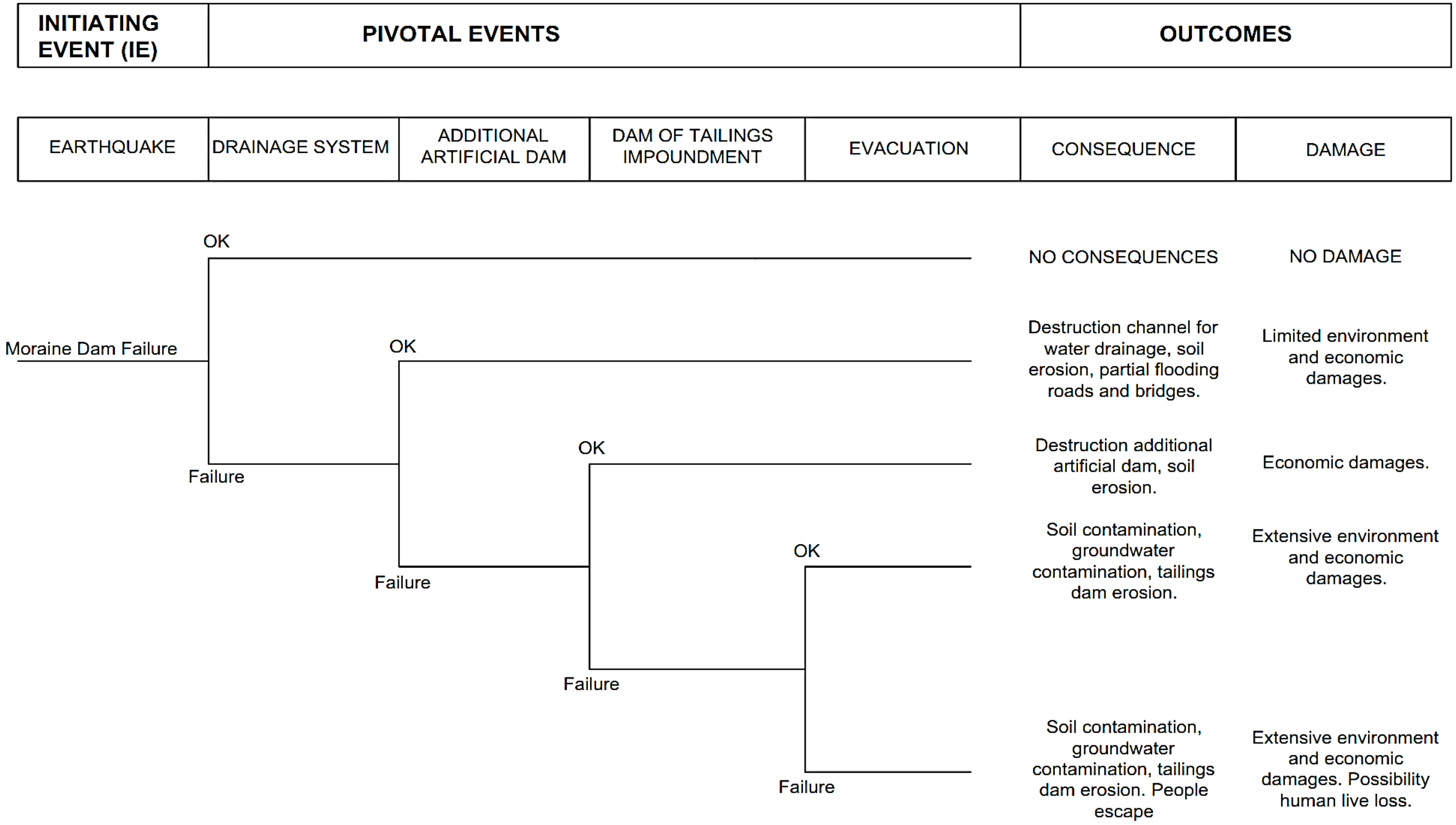


Figure 5.9 Event Tree for Petrov's GLOF consequences associated with earthquake.

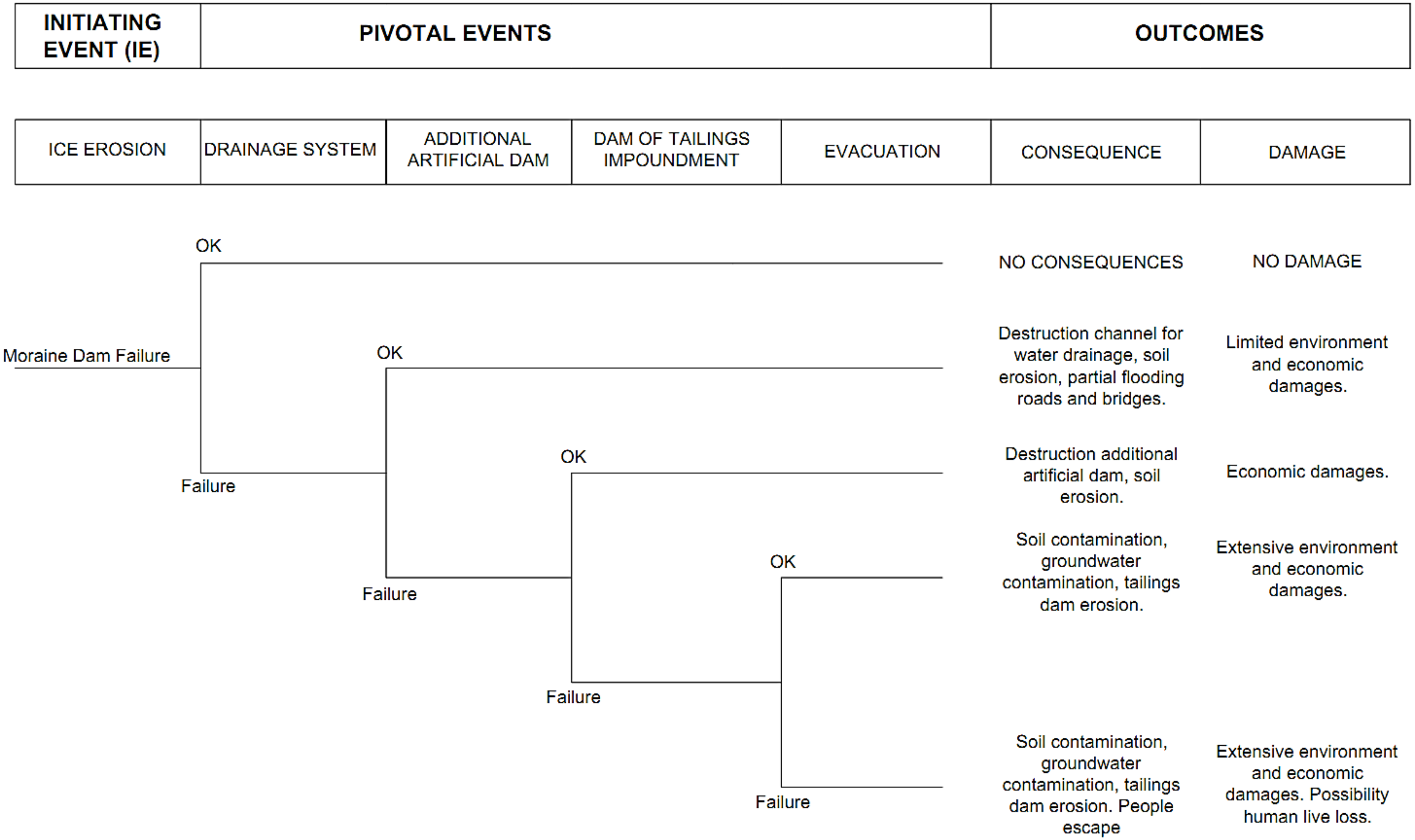


Figure 5.10 Event Tree for Petrov's GLOF consequences associated with ice erosion in the moraine dam.

Tailings pond

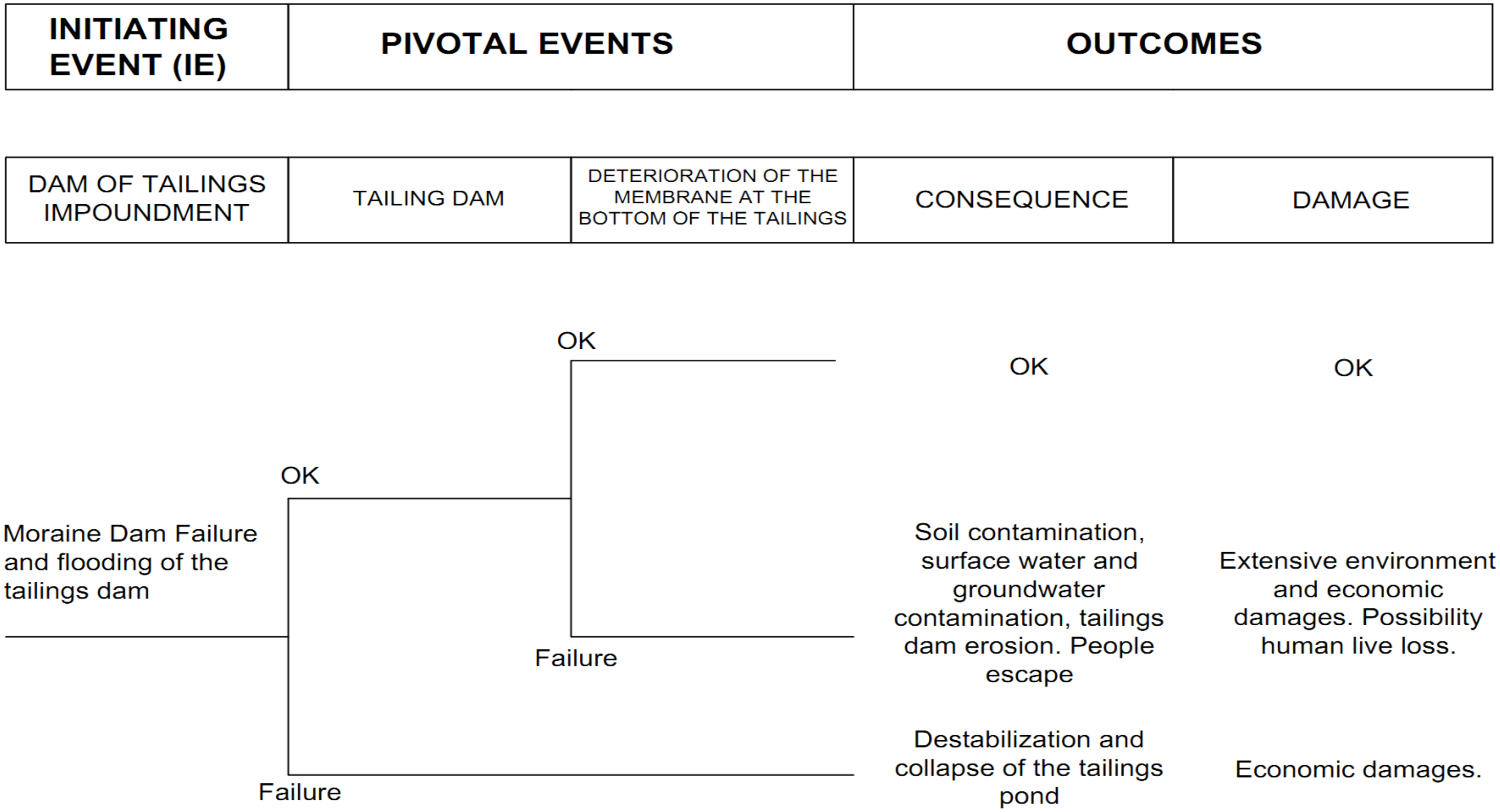


Figure 5.11 Event Tree for tailings pond consequences associated with Petrov's GLOF.

5.2 Risk quantification.

For risk assessment were used initiating events (IE). Also, one of the pivotal event "TAILING DAM" was used. The Pivotal events such as «ADDITIONAL ARTIFICIAL DAM» and «DRAINAGE SYSTEM» depend on the volume of water. They are work if the breakthrough wave of water less than 8000 m^3/s, with a >8000 m^3/s probability of retention breakthrough is minimal or zero.

5.2.1 Estimation of probability.

The risk assessment will be performed for each accident scenario, from the assessment associated with the consequence or effect for each environment.

- **The scenario of GLOF after the increasing water volume on the lake.**

The monitoring of Glacier Lake is totally based on different types and dates of satellite images. The data set images of 1950s, 1980s, 1990s, 2000 and 2006 of Ak Shiyrak glacier were used (Table 3.2.). Least snow cover and cloud free satellite images were selected for lake area measurement. Least snow cover in the Tian Shan occurs generally in the summer season (May-September). But during this season, clouds will block the views. If snow precipitation is late in the year, winter images are also suitable except for the problem of long relief shadows in the high mountain regions. The frozen lake always has a level at the toe of the Petrov's glacier tongue.

The lake area (S) is determined in the same manner as the length (L). The upper (H_1) and lower (H_3) absolutely height of dam (ΔH) allows to determine the height of the dam (Figure 3.3).

$$\boldsymbol{\Delta H = H_1 - H_3 = 3748\ m - 3705\ m = 43m}$$

Table 5.4 Characteristics of Petrov's Lake changing (period 1957-2013).

Year	Dam Height $\Delta H, (m)$	Average depth $\Delta Z\ (m)$	Volume $V\ (m^3)$	Area $S\ (m^2)$	Flow outburst wave. Q_{max}, m^3
1957	43	2,5	960009,9387	960000	168030,2793
1980		3,75	44032005,16	1830000	1733397,305
1990		4,5	56303218,6	2340000	2013838,411
1999		10	67371381,21	2800000	2246825,684
2006		17,5	91432595,67	3800000	2706892,411
2013		18	105869319,5	4400000	2960118,715

All data were taken from the catalog of glacial lakes in Central Asia. Flow outburst wave was calculated by Costa formula:

$$\boldsymbol{Q_{max} = 3.8(\Delta H \cdot V)^{0.61}}$$

Where:
Q_{max} - Flow outburst wave;
ΔH - Dam height;
V - Volume of water;

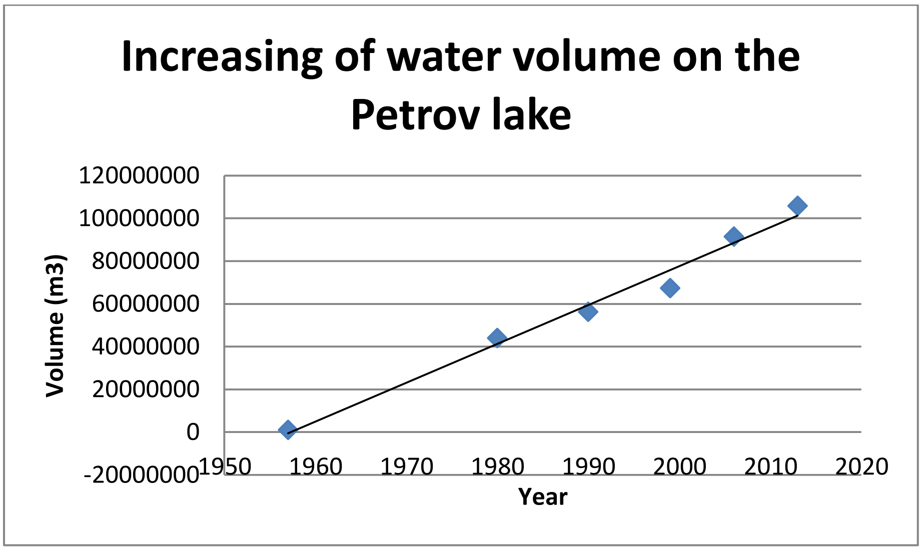


Figure 5.12 Increasing of water volume on the Petrov's lake (period 1957-2013).

In order to predict the probability of GLOF of Petrov's lake, the values in Table 5.5 were used as inputs for *McKillop and Clague's* regression model. Inputting the data presented in Table 5.6 to *Clague's* regression analysis shown in next equation showed the probability of GLOF to be equal to:

$$\boldsymbol{P = \left\{1 + e^{-[\alpha+\beta_1(M_{kW})+\sum\beta_i(ice_{core})+\beta_2(S)+\sum\beta_k(geology_k)]}\right\}^{-1}} \quad (2)$$

Table 5.5 Clague's regression' variables.

№	Variable	Symbol	Value	Unit	Definition
1	Lake area	S	4.4	km^2	Lake surface area
2	Moraine height to width ratio	M_{kW}	43/280 (0.1536)	-	Ratio between moraine height and moraine width.
3	Ice-cored moraine	ice_{core}	1	-	Moraine dam type
4	Main rock type forming moraine	$Geology_k$	1	-	Bedrock lithology surrounding and/or upstream of lake—granitic, volcanic, sedimentary, metamorphic

Note: Values for M_{kW} and S were measured directly from LADSAT 7; ice_{core} is assigned a value of 1 if ice exists in the moraine and 0 if there is none; $Geology_k$ is assigned a value of 1 for granitic, volcanic, sedimentary, or metamorphic material, and 0 for any other material. α is the intercept, $\beta_1, \beta_i, \beta_3, \beta_k$ and are regression coefficients.

Table 5.6 Regression coefficients estimated for the outburst probability model.

Variable	Category	Coefficient
$Intercept$	-	-7.1074 (α)
M_{kW}	-	9.4581 (β_1)
ice_{core}	Ice-free Ice-cored	1.2321 ($\beta_{ice-free}$) -1.2321 ($\beta_{ice-cored}$)
S	-	0.0159 (β_2)
$Geology_k$	Granitic Volcanic Sedimentary Metamorphic	1.5764 ($\beta_{granitic}$) 3.1461 ($\beta_{volcanic}$) 3.7742 ($\beta_{sedimentary}$) -8.4968 ($\beta_{metamorphic}$)

The probability of the outburst was described qualitatively in order to avoid giving the impression of unrealistic precision. This was especially important, since the model was created using a long-term study.

$$\boldsymbol{P = \left\{1 + e^{-[-7{,}1074+9{,}4581*(0.1536)+\sum -1.2321*(1)+0.0159*(4.4)+\sum 3.7742*(1)]}\right\}^{-1} = 0.22 = 22\%}$$

According to the parameters set by McKillop and Clague, a ‘high’ probability of GLOF is defined as one between (0.17) 17% and (0.24) 24%, so our calculations predict a high probability of outburst at Petrov’s Lake.

Table 5.7 Indicators of probability degree for Petrov’s GLOF by increasing of water on the lake.

Probability Category	Probability (%)	Valuation	Description
Very High	25-100	5	Risk event expected to occur
High	19-24	4	Risk event more likely than not to occur
Medium	13-18	3	Risk event may or may not occur
Low	7-12	2	Risk event less likely than not to occur
Very Low	0-6	1	Risk event not expected to occur

- **The scenario of GLOF after the earthquake.**

Another reason of Petrov’s Lake GLOF is seismically active region. Earthquakes are frequently occurring types of natural disasters in the region.

Earthquakes take place unexpectedly and are often followed by secondary phenomena (landslides, rockfalls, fires, etc.). Almost the whole territory of Kyrgyzstan is prone to high seismic hazards. Approximately 20% of the total area of the country (40,000 km^2) is prone to potential earthquakes of high intensity, and in the 158,000 km^2 of the territory (79%) earthquakes of medium intensity.

The Earthquake probability map was created by researchers of Institute of Seismology (Science Academy of Kyrgyz Republic).

The below map of seismic hazards shows the expansion of territories prone to earthquakes with indication of various intensities where four levels of seismic hazard prone areas are identified. Virtually all highlighted zones and subzones in the map represent high degree of risk to the population.

- Level I seismic hazard zones include mountain slopes of high and middle altitude relief layers of Kyrgyz Tien-Shan ridge.
- Level II seismic hazard zones include the low altitude mountain and hillside valleys in the number of intermountain valleys.
- Level III seismic hazard zones include almost all of the valleys in the Kyrgyzstan.
- Level IV seismic hazard zones include high mountainous areas.

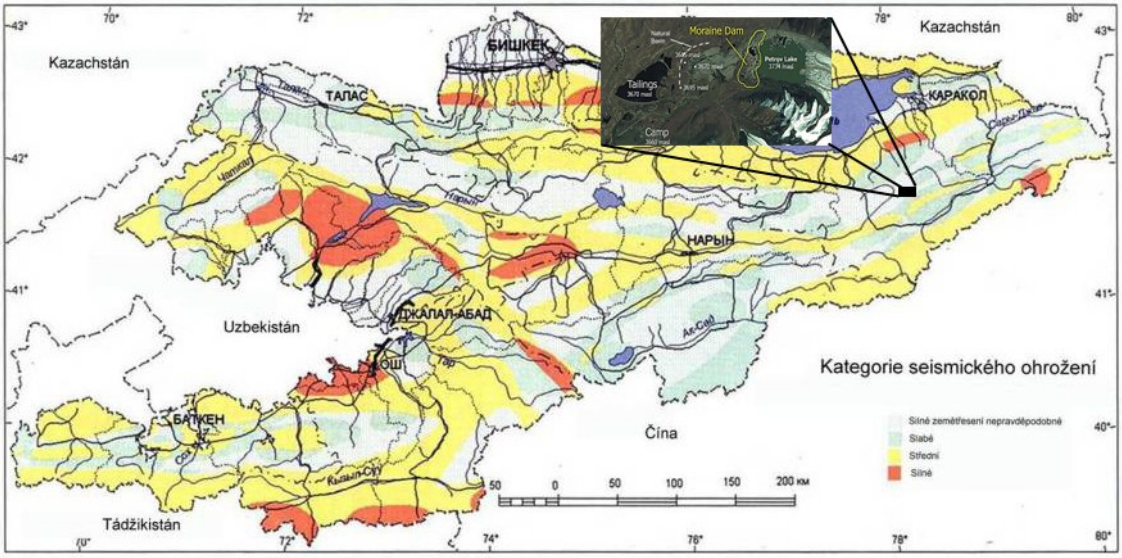


Figure 5.13 Seismic hazard map of the Kyrgyz Republic.

According to the Institute of Seismology Petrov’s lake is located on the territory of "medium" seismic hazard zone.

Table 5.8 Indicators for deriving probability of occurrence for Petrov's GLOF by earthquake.

Probability Category	Probability	Valuation	Description
Very High	🟥	4	Risk event expected to occur
High	🟨	3	Risk event more likely than not to occur
Medium	🟦	2	Risk event may or may not occur
Low	⬜	1	Risk event less likely than not to occur

- **The scenario of GLOF after the ice erosion.**

The Petrov lake's moraine dam has a several thermokarst cracks which weaken the stability of the dam. They are the result of lateral erosion. Long-term underwater movement, exterior temperature, and other processes could create the conditions for occurrence of cracks. Recently appeared on the surface of the dam is another lake. Volume of the lake is 750 000 m^3. Maximal depth is 22 m. Average depth is 8.5 m. This lake can pose a major threat to dam safety.

Every year on the territory of the lake conducted geophysical measurements to monitor the stability of the dam. The latter study shown that the average increase of the crack hydraulic stress is 7.63 N/m^2. This index can be identified by the following formula.

$$\boldsymbol{\tau = \frac{\rho_w \cdot g \cdot H_f^2 \cdot W}{2 \cdot (H_f + W) \cdot L}}$$

Where: τ - hydraulic shear stress in N/m^2
ρ_w - density of water in kg/m^3;
g - acceleration due to gravity = 9.8 m/s^2;
H_f - head loss in crack due to friction in m;
L – length of crack in m;
W – width of crack in m;

In the Table 5.9 showed the data for the last 13 years.

Table 5.9 Petrov's lake dam stability data on the last periods (2001-2013).

Year	Water density $(\frac{kg}{m^3})$	Acceleration due to gravity (m/s^2)	Head loss in crack due to friction (m)	Length of crack (m)	Width of crack (m)	Hydraulic shear stress $(\frac{N}{m^2})$
2001	999,7	9,8	3	8	0,01	6,102819767

2002	999,8	9,8	3	8,2	0,01	5,954566081
2003	999,7	9,8	3	8,5	0,015	8,601457419
2004	999,7	9,8	3	8,5	0,015	8,601457419
2005	999,75	9,8	3,5	9	0,015	8,129783073
2006	999,7	9,8	3,5	9	0,015	8,129376482
2007	999,7	9,8	4	9,4	0,015	7,787599693
2008	999,7	9,8	4	9,6	0,015	7,625358032
2009	999,8	9,8	5	9,8	0,015	7,476071785
2010	999,7	9,8	5	10	0,015	7,325817547
2011	999,7	9,8	5,5	12	0,02	8,134636171
2012	999,7	9,8	6	12,6	0,02	7,749612403
2013	999,7	9,8	6	13	0,02	7,511162791

According to Table of *Bonelli and Brivois* can determine the degree of risk of outburst flood. The average value of the hydraulic shear stress in the range of "very low", it means that haven’t risk on the erosion scenario.

Table 5.10 Approximate estimates of range of shear stress.

Probability Category	**Range of Hydraulic shear stress τ (Pa)**	**Valuation**	**The rate of increase of the crack.**
High	>100	4	Very Rapid
Medium	51-100	3	Moderately rapid
Low	21-50	2	Slow
Very Low	1-20	1	Very Slow

- **The scenario with the tailings pond.**

“Kumtor mine” Tailings Management Facility (TMF) consists of tailings pipelines, tailings dam, Effluent Treatment Plant (ETP), and diversion ditches. The pulp from the Mill is transported by gravity in one of the pipelines (7 km length). The tailings continued to be discharged and contained in a single tailings basin created by the construction of tailings dam across the former river, in the lower part of its valley. A synthetic geo-membrane anti-filtration liner was placed on the upstream side of the dam to prevent erosion, seepage, freezing of dam body.

Figure 5.14 Tailings pond construction.

The reasons for employing geomembranes for containment facilities are all based on the reduction of leakage and the resulting reduction in “failure” risk that comes with better containment; with the definition of “failure” including structural failure, environmental contamination and inadequate water supply.

The most common types of geomembrane typically used in the mining industry are high density polyethylene (HDPE), linear low density polyethylene (LLDPE) and polyvinyl chloride (PVC). These products are listed in order of increasing flexibility and decreasing strength. The thicknesses of the both types of polyethylene (PE) liners typically run from 1.0 to 2.0 mm, while PVC is typically 0.50 to 1.0 mm thick. The high density polyethylene HDPE material used by “Kumtor” mine Tailings Management Facility (TMF) warranted till 30 years. If the first membrane were laid in 1996 then now it is already 18 years old. It is very important to keep in mind. According to that the life cycle of a geomembrane not yet expired. The risk of leakage of pollutants on soil is not large. In this case it is possible to give the "low" range.

Table 5.11 Estimation of the probability for the Petrov lake outburst flood and tailings pond failure.

Accident scenario	Damage	Consequence	Quantity of accidents	Assets and production capital	Affected population	Probability
Rising of water	Flooding camps, bridges, roads, tailings pond. Soil erosion. Environmental losses. Economic losses.	Destabilization of the moraine dam, which will lead outburst a lot of volume of water from the lake.	2	2	2	4
Earthquake			2	2	2	2
Erosion			2	2	2	1
Tailings pond failure	Pollution of ground water, soil, flora, fauna and people.	Seepage of pollutants through the geomembrane.	4	4	3	2

5.2.2 Estimation of consequence.

The materialization of a risk can lead to different consequences. For this reason, the estimate of the result shall be based on the impact of environmental liability on health, environmental quality and safety of the population.

The estimation of the consequences is determined by the sum of the values obtained in the following variables:

- Quantity - The quantity is determined according by the analysis of the variables "quantity of waste", which will get into the Naryn river from tailings pond.

Table 5.12 Scale of "quantity".

Quantity of waste	Quantity	Range
>500 tones	Very High	4
50-500 tones	High	3
5-49 tones	Medium	2
<5 tones	Low	1

- Hazard - is understood as an intrinsic ability of the substance to cause harm, its toxicity, its potential accumulation.

Table 5.13 Scale of "hazard".

Hazard	Hazard evaluation	Range
Very toxic	Very High	4
Toxic	High	3
Low toxic	Medium	2
No toxic	Low	1

- Extension is a factor is based on the distance between the person and the people who are potentially affected.

Table 5.14 Scale of "extension"

Extension	Extension	Range
Presence of population is located in the same place of accident.	Very Extensive	4
Presence of population is within a radius <0.5 km	Extensive	3
Presence of population is within a radius 0.5 - 1 km	Low Extensive	2
Presence of population is within a radius >1 km	Not Extensive	1

- The Quality of the environment is determined depending on the reference standard set.

Table 5.15 Estimation of quality of the environment.

Quality of the environment	**Range**
Very High	4
High	3
Medium	2
Low	1

- Affected population is based on the number of people who are potentially affected at risk.

Table 5.16 Determination and estimation of affected population.

Affected population	**Range**
>100	4
25-100	3
5-25	2
1-5	1

- Assets and production capital is based on the total cost of constructions, roads, bridges which are potentially affected at risk.

Table 5.17 Determination and estimation of affected assets and production capital.

Assets and production capital	**Range**
Very High	4
High	3
Medium	2
Low	1

5.2.3 Estimation of damage.

Table 5.18 Estimation of the damage for the Petrov lake outburst flood and tailings pond failure.

Accident scenario	**Damage**	**Quantity**	**Hazard**	**Extent**	**Quality of environment**	**Assets and production capital**	**Affected population**	**Damages of the NE**	**Damages of SE**	**Damages of the HL**
Rising of water	Flooding camps, bridges, roads, tailings. Soil erosion. Environmental losses. Economic losses.	3	3	1	2	2	2	10	12	12
Earthquake		3	3	1	2	2	2	10	12	12
Erosion		3	3	1	2	2	2	10	12	12
Tailings pond failure	Pollution of ground water, soil, flora, fauna and people.	4	4	3	4	3	2	19	18	17

5.2.4 Risk estimation

The estimation of the severity is made from the Table 4.7 Scales of severity estimation.

When the quantification of risk for each scenario at each site will be observed:

Table 5.19 Risk quantification of the Petrov glacier lake outburst flood.

Accident scenario	**Damage**	**Probability**	**Damage**			**Severity**	**Risk**	
			Damages of the NE	**Damages of SE**	**Damages of the HL**		**Value**	**Range**
Rising of water	Flooding camps, bridges, roads, tailings. Soil erosion. Environmental losses. Economic losses.	4	10	12	12	3	12	Medium risk
Earthquake		2	10	12	12	3	6	Moderate risk
Erosion		1	10	12	12	3	3	Low risk
Tailings pond failure.	Pollution of ground water, soil. flora, fauna and people.	2	19	18	17	5	10	Moderate risk

Risks categorized on a scale, with the code, which includes guidance.

Table 5.20 Scale of risk evaluation.

Risk evaluation		
Very high risk	21-25	🟫
High risk	16-20	🟥
Medium risk	11-15	🟧
Moderate risk	6-10	🟨
Low risk	1-5	⬜

The estimation of rik for each scenario was performed as multiply the probability {1-5) by the severity of the consequences {1-5), resulting in a value between 1 and 25, where 1 the lowest risk and 25 the highest risk.

Table 5.21 Location of risk, the probability and severity for the accident scenarios.

		Probability				
		1	2	3	4	5
Severity	1					
	2			GLOF from Earthquake		
	3	GLOF from Erosion			GLOF from Rising of water	
	4					
	5		Tailings pond failure			

6. CONCLUSIONS

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.

To solve these problems requires perform some conclusions presented in this thesis.

- Monitoring of lake and tailings pond.

Monitoring GLOF hazard levels requires a multi-staged, interdisciplinary approach using multi-temporal data sets. Key indicators include changes in the lakes and their impoundments which should be observed using different data sets at varying time scales to evaluate glacier hazard and stability of moraine dams. Also, must to control exterior factors which affect to Kumtor tailings pond.

- Artificial reduction of water in the lake.

The most important mitigation measure is to reduce the volume of water in the lake, thus reducing the magnitude of the possible peak discharge at the time of breach. Structural mitigation measures can also be applied downstream to protect infrastructure from peak floods.

The volume of water can be reduced by means of one or more of the following: controlled breaching of the moraine dam; construction of an outlet control structure; pumping or siphoning the water from the lake; and tunnelling through the moraine barrier or under an ice dam.

Preventative measures can also be carried out around the lake to secure against potential threats such as loose rocks or snow/ice avalanches that could trigger displacement waves.

- Awareness Raising.

The local community needs to become more aware of GLOF hazards and ways and means to respond to warnings. It is important to continue dissemination of accurate information to the public, and raising of public awareness on glacial lakes and GLOF risk management, through a variety of means such as press reports, TV programmes, radio programmes, news articles, and scientific forums for public awareness.

- Need for a National Policy

In view of the very high, if unpredictable, hazard involved, it is imperative that a national policy be developed for increasing awareness, early warning, and risk mitigation. This could then be used as a template for application to the entire Tien Shan region. Furthermore, immediate action is urged along the following lines: increase of public awareness; more extensive vulnerability assessment; routine airborne and satellite monitoring; and more intensive and repeat geophysical survey. There also remains the inherent danger of trans-international level that requires international cooperation. Region-wide cooperation throughout the Central Asia should follow, and it is recommended that steps be taken to organise a region-wide planning session for experts and leaders of relevant national institutions to develop a more coordinated approach and begin laying the foundations for a glacial lake outburst risk reduction policy.

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