Czech University of Life Sciences Prague

Faculty of Environmental Sciences

Department of Land Use and Improvement

DIPLOMA THESIS

ANALYSIS OF LANDSCAPE CHANGES INDUCED BY HIGH MOUNTAIN GEOHAZARDS BY MEANS OF REMOTE SENSING

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DIPLOMA THESIS ASSIGNMENT

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Landscape Planning

Thesis title

Analysis of landscape changes induced by high mountain geohazards by means of remote sensing

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Objectives of thesis

Main goal of this thesis is to assess landscape changes in selected locations in the Kyrgyz part of Tien Shan mountain range, caused by development of glacial lakes and glacial lake outburst floods. Mainly the remote sensing data and their GIS analyses will be used in the thesis.

Methodology

The first part of the thesis describes realized surveys about glacial lake outburst flood events in the Central Asian mountain ranges and in the European Alps. The study area is located in Sary Jaz river basin in the Tien Shan mountains in Kyrgyzstan and China. The periodically outbursting ice dammed Merzbacher Lake in Inylchek glacier is selected as target of our research. It evaluates historical events of outburst and its consequences in landscape. For practical part of the thesis the remote sensing data and their GIS analyses and interpretation are used. Satellites imagery acquired since 1970 are the source of the data.

The proposed extent of the thesis

40 – 60 pages

Keywords

Glacial lake, ice-dammed lake, glacial lake outburst flood, glacier retreat, remote sensing, river basin, Tien Shan, Kyrgyzstan

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Recommended information sources

A century of investigations on outbursts of the ice-dammed lake Merzbacher (central Tien Shan)
Attribution of global glacier mass loss to anthropogenic and natural causes
Encyclopedia of snow, ice and glaciers
Evolution of a high mountain thermokarst lake in the Swiss Alps
Glacier changes in the central and northern Tien Shan during the last 140 years based on surface and remote-sensing data
Identification of potentially dangerous glacial lakes in the northern Tien Shan
Outburst flood hazard Case studies from the Tien Shan Mountains Kyrgyzstan
Symposium: High-Mountain Lakes and Streams: Indicators of a Changing World

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Declaration:

I declare that I have worked on my diploma thesis titled "Analysis of landscape changes induced by high mountain geohazards by means of remote sensing" by myself and I have used only the sources mentioned at the end of the thesis. As the author of the diploma thesis, I declare that the thesis does not break copyrights of any their person.

Prague, 17th April 2017 ……………………………………

Abstract

In the context of climate changes melting of ice caps and glaciers occur on global scale. Mountain glaciers retreat creates environment for occurrence of glacial lakes and their expansion. In Tien Shan mountain range, there are hundreds of glacial lakes with the risk of glacial lake outburst flood, many of them already outbursted. Some ice dammed lakes like Merzbacher Lake located between South and North Inylchek Glaciers in central Tien Shan outburst periodically. This thesis is focused on landscape changes caused by GLOF of Merzbacher Lake, especially changes of the North Inylchek glacier, shape of the Inylchek Valley, and the whole Sary Jaz river basin. The research uses remote sensing data from the past 40 years in wide scale. The main data source are data collections especially from Landsat satellites from the past 40 years. The work contributes and provides some new facts and proves theories about consequences of GLOFs in landscape.

Keywords

Glacial lake, ice-dammed lake, glacial lake outburst flood, glacier retreat, remote sensing, river basin, Tien Shan, Kyrgyzstan

Content

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List of abbreviation

BRGM	Bureau de Recherches Géologiques et Minières
CAD	Computer aided design
CNRS	Le Centre national de la recherche scientifique
DEM	Digital Elevation Model
EIS	Extreme Ice Survey
ETM+	Enhanced Thematic Mapper Plus
GDP	Gross domestic product
GEE	Google Earth Engine
GEEE	Google Earth Engine Explorer
GIS	Geographic Information System
GLOF	Glacial Lake Outburst Flood
GNSS	Global Navigation Satellite System
LGGE	Laboratoire de Glaciologie et Géophysique de l'Environnement
NASA	National Aeronautics and Space Administration
NDWI	Normalized Difference Water Index
RTM	Restauration des terrains de montagne
SLC	Scan Line Corrector
USGS	United States Geological Surve

1 Introduction

Mountain glaciers have affected the landscape all over the Earth or thousands of years. Glaciers not only transport material as they move, but also shape and carve whole mountain ranges. It heavily affects mountain slopes, valleys, foothills, river basins, and last, but not least, even cultural land under the mountains. Glaciers in high mountain areas are considered as obvious indicators of climate change. An example would be Mountains of Tien Shan. In the past decades, the global climate warming caused glaciers to melt and retreat all around the world.

We can observe glacier recession in the Greenland, Alaska, Alps, Iceland, Norway and other regions. These processes are obvious in the mountains of central Asia too. In the past decades, glacier retreat caused landscape changes in the mountain ranges very quickly. Glaciers and its outflow water change the water regime in river basins. The consequence of melting glaciers is increased flow of water volume into the mountain lakes. The dams of the lakes, formed by unsolid rubble of moraines are collapsing under the water pressure (Janský, 2015).

This diploma thesis provides an overview of glacier retreating in Kyrgyzstan with regards to the landscape changes of its river basins. It will focus on fields of landscape changing, erosion, water management and consequent geohazards, especially glacial lake outburst floods (GLOF), specifically on the Lake Merzbacher in Tien Shan, Kyrgyzstan.

1.1 Goals

The main goal of this thesis is to assess landscape changes in selected locations in the Kyrgyz part of Tien Shan mountain range, caused by development of glacial lakes and glacial lake outburst floods. Mainly the remote sensing data and their GIS analyses will be used in the thesis.

The goal is to describe landscape changes in Inylchek and Sary Jaz / Aksu river basin caused by periodically bursting ice dammed Merzbacher Lake, with help of satellite imagery. Historical research about the events in selected area for last century will be evaluated and selected GLOF events since 1970 will be verified. The influence of the glacial lake outburst flood on the shape of Inylchek Glacier, floodplain of Inylchek Valley and rest of the Sary Jaz / Aksu river basin towards Chines Taklamakan Desert will be assessed.

2 Glacial lakes type

We distinguish many types of glacier shaped objects. The bigger one, like: cirques, arêtes, horns and fjords. And smaller one, like: Moraines, drumlins, kettles, kames and other fluvioglacial landforms.

Moraine is a type of landscape formation, developed by glacier activity. It is located in mountains around mountain glaciers. It contains boulders, stones, debris and all kinds of gravel. We distinguish moraine in a front of the glacier, called terminal moraine or moraine besides of glacier.

One of the objects this thesis is focused on are glacial lakes. Glacial lake is a type of lake whose origin is associated with the development of the glaciers. (Falátková, 2014). It has very progressive development in times of global warming so there is high risk of natural disasters called lake outbursts. We distinguish several types of glacial lakes. Very practical overview of glacial lakes was provided in Kristýna Falátková´s diploma thesis (Falátková, 2014).

2.1 Proglacial lakes

Main type of glacier lake is proglacial lake which is located before glacier terminus. The dams and bottoms of the proglacial lakes are often formed by moraine, debris of moraine and residue ice from retreated glaciers. Lakes are called moraine-dammed lakes. The cumulated water is relatively hot in the summer and causes another melting of head of the glaciers and residue ice in lake dams which is just increasing the risk of their rupture.

2.2 Supraglacial lakes

Second main type of glacial lakes is supraglacial lake. The main indicator is that supraglacial lakes develop on the surface of the glacier, mainly in the flat areas of the glacier. According to Janský, *Supraglacial lakes develop on the surface of glaciers. Outflow from the lake is either surface or through the underground channels. More rapid bursts occur in case of surface outflow. Supraglacial lakes with periodical filling are the most dangerous. They develop in closed depressions with underground outflow where the active basin development is already finished. When under-ground channels get blocked up, the lake fills quickly and the risk of outburst increases*. (Janský, 2009). Supraglacial lakes could indicate also negative mass balance of the glacier (ablation) more than glacier terminus retreating (Falátková, 2014).

2.3 Subglacial lakes

Subglacial lakes are lakes under a glacier. They do not typically occur under mountain glaciers but in polar regions, under the ice caps (Island or Antarctica ice sheet). Subglacial lakes studies are strong phenomenon of glaciology especially in Iceland because of glacier–volcano interactions. Accumulated meltwater drains periodically in jökulhlaups, which is islandic term for supraglacial lake outburst (Björnsson, 2002).

It is very difficult to discover and observe these types of lakes. Remote sensing, very strong method for glaciology, have very limited use in the field of supraglacial lakes investigations. Magnetic resonance imaging or fluorescence spectroscopy is ones of few methods used in lake investigations (Vincent, 2003). That makes jökulhlaups very unpredictable and they have catastrophic consequences (Falátková, 2014). Advance investigation about supraglacial lakes is given by scientists (and by all involved workers who have very difficult job) from Laboratoire de Glaciologie et Géophysique de l’Environnement (LGGE) who publish the reanalysis of jökulhlaups of Glacier de Tête Rousse in 1892 (Vincent, 1892).

2.4 Lakes dammed by landslide, rockfall, debris flow and rock step

These types of lakes are not connected directly with mountain glaciers behaving. However, Bohumír Janský describes this type of lakes in his research

Outburst flood hazard: Case studies from the Tien-Shan Mountains, Kyrgyzstan and *Typology of high mountain lakes of Kyrgyzstan with regard to the risk of their rupture*, where he was evaluating its risks of collapses.

2.5 Moraine-dammed lakes

Moraines are developing in consequence of glacier move from top of the mountains, through foothills, to the mountain valleys, even to mountain foothills. In this process glacier pushes and moves rock material down from the upper parts of the mountains. Today we can observe opposite process. The glaciers are melting and retreat from valleys towards foots of mountains. The melting of glaciers produces more and more water which is retained in the space between created moraine and missing glacier. That is called moraine-glacier lakes formation. According to Janský, this type of lake is represented by Petrov lake in Kyrgyzstan.

2.6 Glacier-dammed lakes

The dam of glacial lake can be also formed by another glacier. These dams are very specific because they are developing constantly and quickly. Drainage channels into the glacier are very changeable. They are shrinking and extending during the change of glacier formation and due to change of hydrological pressure from the lake. Dams collapse for several reasons. One of the reasons is the ice dam buoyancy effect, when the glacial dam is uplifted by water with higher density from bottom up to the lake level. The lake upholds its own dam and burst out of glacier. This process happens usually periodically in period of days in Hidden Creek Lake (Walder, 2005) or in period of years like in Lake Merzbacher (Glazirin, 2010).

Very representative example of glacier-dammed lake is Hidden Creek in the USA (Walder, 2005) and Lake Merzbacher in Kyrgyzstan on which this thesis will focus on ongoing parts.

2.7 Thermokarst lakes

Thermokarst lakes are typical for arctic regions, but they are rarely found in mountain areas also. It is characteristic landform for ice-rich ground and low relief areas such as ice-rich permafrost or glacier ice. They typically develop in depressions created by the melting of buried ice in permafrost or in glacier moraines. These lakes usually block natural outlet and can be serious threat for stability of the moraine dams. From time to time, it can burst into the cavity in the permafrost or into the subglacial channels in the glacier and it can leave behind the sinkhole or dead-ice hollows (Kaab, 2001). Thermokarst lakes occur most often in small groups of many and they are located on the periphery of glaciers and its horizontal areas in glarier lower partitions.

3 Glaciers change

Planet Earth faces global warming. As one of planetary boundaries, global warming affects Planet Earth in many ways, not just simply with increasing temperature. Jenifer A. Elliot says in her book An introduction to sustainable development, that *the major effects of climate warming will relate to water resources: through the rise of sea levels as a result of the thermal expansion of the oceans, the melting of glaciers and ice-sheets, and increased precipitation…* (Elliot, 2006). Mountain glaciers are very significant indicator of global warming. Alpine glaciers retreat which means that the position of a mountain glacier’s terminus is farther up valley than before. Glacial retreat occurs when a glacier ablates more ice at its terminus than it transports into that region. (Singh, Shrestha, 2011). It has negative mass balance.

Glaciers retreat since last glacial maximum 21 thousand years ago, when glaciers covered up to 30% of the land (Singh, Shrestha, 2011). Later, the glaciers faced general warming since the Last Glacial Maximum to the early Holocene, about 10 000 years before. This warming brought drastic general glacier shrinkage. Colder climate brought medieval times. The period from 14th century to 19th is called the Little Ice Age.

3.1 Glacier mass balance

Mass balance is difference between accumulation and ablation of a glacier in a given time interval. Mass balance response changes in atmospheric conditions such as: solar radiation, air temperature, precipitation, wind and cloudiness (Singh, Shrestha, 2011). There is significant link between climate processes and glacier mass balance (Oerlemans, 2005). Shrestha also evaluates, that based on the paleoclimatic evidence it is clear, that climate change and glacier fluctuations are closely connected phenomena. But what is not clear is how the glacier retreat is influenced by human activity. Ben Merzeion distinguishes anthropogenic and natural causes of global glacier mass loss. He estimates that *only 25 ± 35% of the global glacier mass loss during the period from 1851 to 2010 is attributable to anthropogenic causes. Nevertheless, the anthropogenic signal is detectable with high confidence in glacier mass balance observations during 1991 to 2010, and the anthropogenic fraction of global glacier mass loss during that period has increased to 69 ± 24%.*

Glacier mass balance is the most relevant index of glacier retreating, more relevant than retreating of the glaciers tongue, which could be misleading. But either way, we have to count with period of ablation (summer) and period of accumulation (winter) and also accumulation and ablation zones in different parts of the glacier. Measuring of Glacier mass balance is long term process. For equal measuring it is very important to set the equilibrium line - the line between ablation area and accumulation area. We have 3 main methods of measuring the mass balance of the glacier (Haag, 2004).

- **Glaciological method**

Classic method which allows us to determine glacier mass balance is measuring summer height of the upper parts of the glacier horizon (snow and firn) and the material density. Measurements are carried out every year, usually in summer (ablation period). Checking indicators are thickness and density of the samples. Practically the stokes, probes or snow pits are used. The More samples in more places of the glacier we have the more precise results we can obtain (Mayo, 2004).

Stokes are installed for a long time in depth of several meters in the ice, and the top of the stokes is kept above the surface. Accurate, but inefficient glaciological method of measuring glacier mass balance is digging a snow pits. It is very easy method, but rather not reliable (Mayo, 2004).

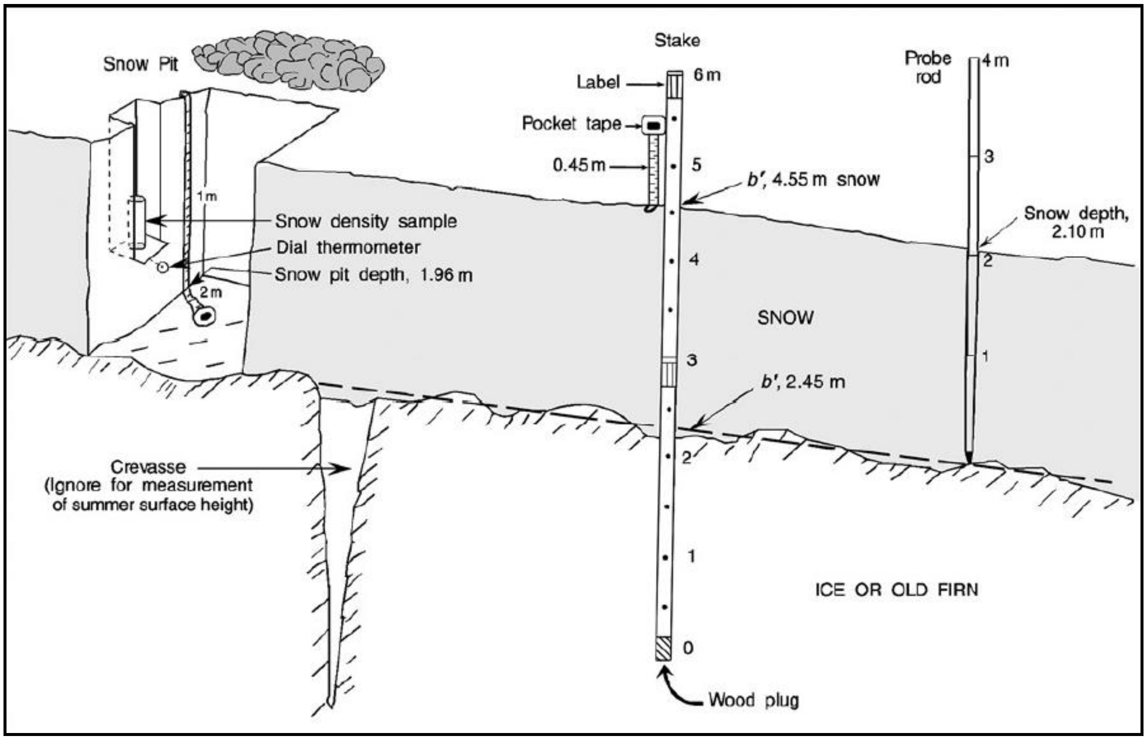


Fig. 1 Mass balance measurement site showing snow pit, stake, and probe measurements (Source: Mayo, 2004)

- **Geodetic method**

Geodetic method is based on collecting the special data and their analysis. We can operate only with the volume of the glacier which is changing in time. For collecting the data, we can use classical tachymetry measuring, GNSS (Global Navigation Satellite System) data collection, aerial photogrammetry or laser scanning (also possible terrestrial or aerial). Final result is given simply by comparison of final topographic maps or digital elevation models (DEM). Disadvantage of this method is distortion of spatial data by glacier natural flow. Geodetic method has another risk of errors like different scale of the maps, quality of the photographs, surface conditions on the glacier, the quality of the geodetic network and in the past, paper map shrinkage and drafting. Wrong densities for converting ice volume to water equivalent could be another source of errors. Despite that, this method is good for long term changes (Haag, 2004).

- **Hydrological method**

Hydrological methods of measuring glacier mass balance need specific infrastructure in the glacier area such as gauging stations. The gauging station serves for measuring precipitation and water runoff to get the data. Than it is necessary to use hydrological model runs in computer. This method could be appropriate, only if we have accurate input data to run the models (Haag, 2004).

3.2 Glacier tongue retreat

Very demonstrable evidence of mountain glacier development and retreating is provided by James Balog´s program Extreme Ice Survey (EIS). *Using both time-lapse and conventional photography as well as digital video, the Extreme Ice Survey is the most extensive visual study ever conducted to illustrate the catastrophic melting of glacial ice. The result is a dramatic and timely demonstration of global warming's dangerous consequences from Alaska to Iceland to the Alps* (Balog, 2009).

James Balog and his project team started in 2007 with installation of the time-lapse cameras, facing to glaciers and taking shots every hour for years. Final time-lapse videos show glacier melting and terminus retreating with no doubts.

We have 43 Nikon cameras watching over 24 glaciers in Antarctica, Greenland, Iceland, Alaska, Canada, Austria, and the Rocky Mountains. Our cameras record changes in the glaciers every hour, year-round during daylight, and yield approximately 8,000 frames per camera per year. We combine these images into stunning time-lapse videos that reveal how quickly climate change is transforming large regions of our planet (Balog, 2009).

One of the EIS localities is Sólheimajökull glacier in Iceland. The glacier terminus retreating and also proglacial lake development are obvious phenomena in these pictures from time-lapse sequence from April 2007 to July 2015.

Fig. 2 Sólheimajökull Glacier terminus retreating between April 2007 to July 2015 (Source: EIS)

Mountain glaciers are relatively fast changing elements of landscape. Its development is often accompanied by many natural risks. Tian Shan range faced many natural geohazards such as landslides, debris flows, floods and glacial lake outbursts. Relatively rapid retreat of glaciers is causing extreme increase of river flows in summer and also overcharging of glacial lakes. Buried melted ice in moraine dams just increases the risks of its destabilization. The consequences of these processes are making collapses of its dams and outbursts of the glacial lakes more common

3.3 Risks of glacial lakes outbursts

Glacier lakes outbursts are very difficult to predict and they can affect very large areas. GLOF can cumulate huge amount of material and can destroy riverbeds, river basins and even cultural landscape and settlements in the foothills.

To predict or prevent catastrophes, it is necessary to monitor glacial lakes. Professor Janský from Charles University in Prague and his team has been studying the risks of Kyrgyz glacial lakes for years (Janský, 2009). In Kyrgyzstan, there are hundreds of Alpine lakes which have grown, and represent natural risks. According Janský´s research from 2009, 328 lakes are at risk of outburst and 12 lakes are considered as actually dangerous. The moraine glacial lakes are considered as the most dangerous type including 47% of listed lakes (Janský, 2006). Janský and his team described 3 main sites in Kyrgyzstan: Petrov lake (proglacial / moraine-dammed), Koltor lake (morainic), Lower Adygine lake (supraglacial).

Very useful method for monitoring glacial lakes is using of remote sensing data. It is also practical, because it is often difficult to get to the side into the mountains with necessary tools. There are several examples of the researches done using remote sensing data for glacial lakes monitoring:

- Bormudoi, 2012 Studying the outburst of the Merzbacher lake of Inylchek Glacier Kyrgyzstan with Remote Sensing and field data
- Xie, 2013 Index for hazard of Glacier Lake Outburst flood of Lake Merzbacher by satellite-based monitoring of lake area and ice cover
- Shabunin, 2012 Studying the outburst of the Merzbacher Lake of Kyrgyzstan using satellite images and field data
- Shangguan, 2014 Elevation changes of Inylchek Glacier during 1974-2007, Central Tian Shan, Kyrgyzstan derived from remote sensing data
- Changes in Merzbacher Lake of Inylchek Glacier and Glacial Flash Floods in Aksu River Basin,Tianshan during the Period of 1903-2009
- Hausler, 2016 Remote-sensing-based analysis of the 1996 surge of Northern Inylchek
- Wang, 2013 Wide expansion of glacial lakes in Tianshan Mountains during 1990-2010

Field example how to deal with threat of GLOF shows glaciologists and engineers on Glacier de Tête Rousse, Mont Blanc – French Alps in following chapter.

According to Wang, the wide expansion of glacial lakes was recorded in Tien Shan Mountains during 1990-2010. His team assessed Landsat TM/ETM images from last 20 years and figured out that glacial lakes of Tien Shan Mountains expanded for about 0,8%. It is caused by regional warming according to the article. The expansion hits pronouncedly the small lakes (<0,6 km²) in altitudes from 3500 m to 3900 m (Wang, 2013). Even more expansion was discovered by Wang in Chinese Himalayas in his other work *Rapid expansion of glacial lakes caused by climate and glacier retreat in the Central Himalayas*. In result he confirmed the thesis that: *The results presented in this* *study confirm the significant role of glacier retreat on the evolution of glacial lakes (Wang, 2014).*

The several GLOFs already affected foothills of Tien Shan, in Kyrgyzstan and Kazachstan. Some of them released massive volume of water and multiplied transported volume. For example, Proglacial lake Kishi, Almaty, Khumbel river basin right inflow of Ulken Almaty, Kaskelen river basin, etc. (Bolch, 2011). Janský also said for Vesmír magazine that *every year, a few glacial lakes collapse in Kyrgyzstan and it endangers villages and cities close to the river basin. Even in the surrounding of Bishkek capital city there are several dangerous lakes, which rupture from time to time. Just last year the flood was in the city center after rupture of Testor Lake (Despite small volume of the lake the flood transformed into a debris flow with estimated max discharge of 300 m³/s. Ala Archa channel (downstream of Testor) 4 hours after the lake drained. The flood was recorded in 40 km distant capital). During other recent rupture, the village located lower along the stream was destroyed while the disaster caused death of more than hundred people. And when stone or mud flows roll along the valley, there is no protection.* (Janský, 2015)

Identification of dangerous glacial lakes in Tien Shan was also interesting for Tobias Bolch in his study *Identification of potentially dangerous glacial lakes in the northern Tien Shan*. With help of satellite data, Bolch detected and analyzed many glacial lakes in his article.

4 Global examples of GLOF

Besides examined Lake Merzbacher, it would be useful to compare other cases of glacial lake outburst with different context and from different areas.

4.1 Glacier de Tête Rousse

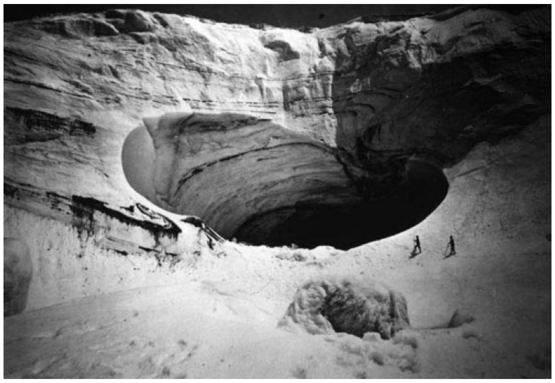
The Glacier de Tête Rousse is small glacier of 0,08 square kilometers of area located in the massive of Mont Blanc - French Alps, on southwest face of the mountain in the elevation about 3 300 meters above sea level (Vincent, 2010). In 1892 subglacial lake outburst devastated Saint-Gervais-Le Fayet, the village near Chamonix.

Disaster preceded increased rate of ablation followed by the creation of supraglacial lake on the surface of the glacier. This lake was covered by snow and it increased its water volume under the surface of the glacier. The glacier terminus was under water pressure from inner lake and then collapsed in the night from 11th to 12th July. The 40 meters wide and 20 meters high cavity released about 100 000 m^3 of water and another 20 000 m^3 of ice and snow from the missing cavity supplied the final volume. The collapse caused another sinkhole in the middle part of the glacier, just above cavity which remained after water was released. The upper cavity was 50 to 27 meters big, and it contributed with another 80 000 m^3 of material to outcoming volume (Vincent 2010).

The total volume of water, ice, snow and debris drained out of the glacier was estimated at 200 000m^3 (Vincent, 2010). This mass flowed to the Torrent de Bionasay, which flowed in to the Le Bon Nant river and its valley. The mass flooded the Bionnay village on the confluence between Le Bon Nant and Torrent de Bionasay. Even the buildings in Saint-Gervais and Le Fayet were destroyed. It was one of the deadliest disasters ever caused by a glacier, it killed 175 people.

The catastrophe was described later by Joseph Vallot, in article The Catastrophe of Saint-Gervais (12-13 July 1892). After the catastrophe, Vallot estimated that subglacial lake will be formed again and recommended to do some technical measurements to prevent another water cumulation and outburst flood. Among other options It was considered blowing up the bedrock, which dammed up the glacier. Finally, the hole was drilled into the glacier to drain water from inner lake in 1904. (Vallot, 1892)

The glacier behavior is still observed today by the modern methods like magnetic resonance imaging or fluorescence spectroscopy. Following a study examining the usefulness gallery drilled in 1904. Appeared in Laboratoire de Glaciologie et Géophysique de l’Environnement (LGGE) new pocket full of water inside the glacier, needed maintenance to avoid the risks of glacier outburst. In 2010 the investment was made to the prevent siren warning system to help the evacuation of the threatened area. Periodic water pumping was done in 2010, 2011 and 2012. Another studies were published by Bureau de Recherches Géologiques et Minières (BRGM), Restauration des terrains de montagne (RTM) and Le Centre national de la recherche scientifique (CNRS) (Vincent, 2010).



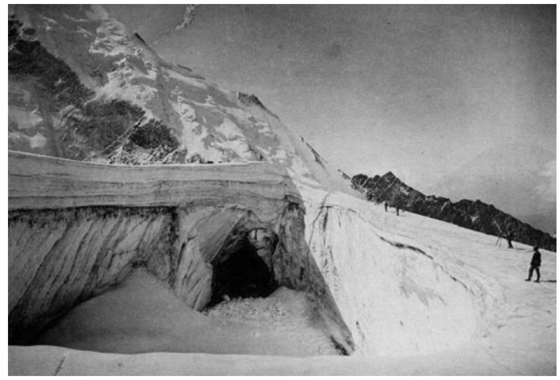
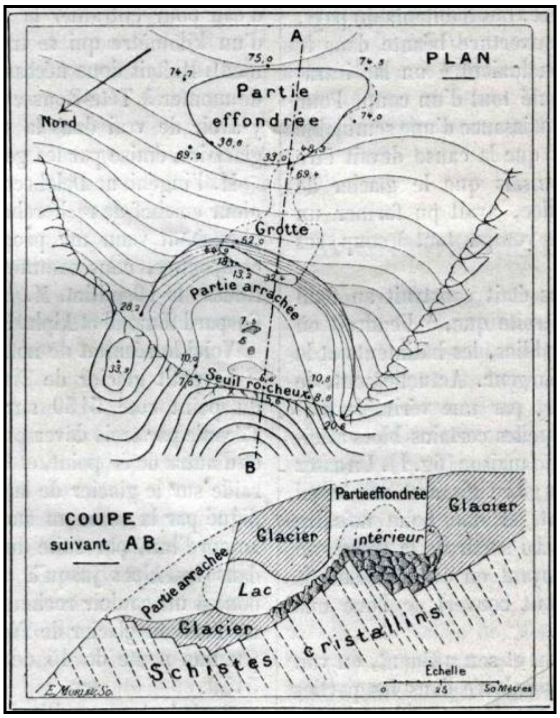


Fig. 3 The Lower cavity (Source: H. Pelloux) / **Fig. 4** The Upper cavity (Source: M. Kuss)



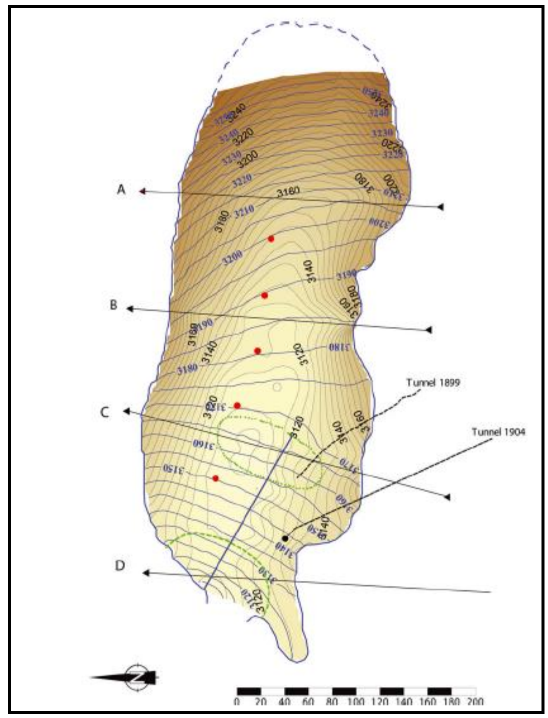
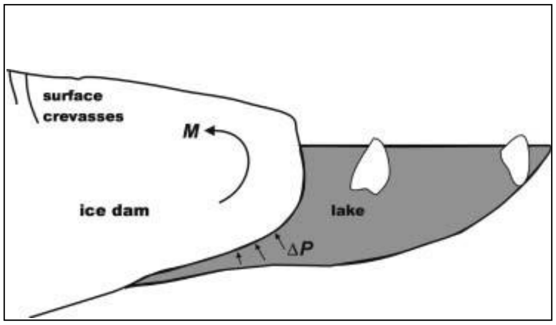


Fig. 5 Section and situation (Source: Vallot) / **Fig. 6** Map of surface and bedrock topography in 2007 (Source: Vincent)

4.2 Hidden Creek Lake

Joseph S. Walder described the ice-dammed Hidden Creek Lake development in Alaska in his article Fault-dominated deformation in an ice dam during annual filling and drainage of a marginal lake (Walder, 2005). The lake is similar to bigger Lake Merzbacher in many ways. Hidden Creek is an ice dammed lake, uplifting its ice dam and it is bursting annually for about 2–3 days. Walder described influence of hydrostatical pressure to the ice dam of the lake as a main cause of the dam collapse, also known as already mentioned ice dam buoyancy effect.



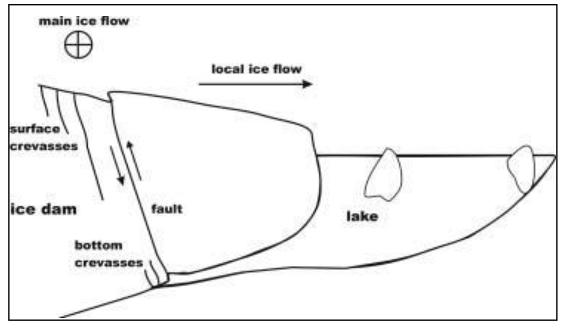


Fig. 7 Schematic cross-sections through the ice dam and lake / **Fig. 8** Relationship between ice-dammed lake and ice dam - ice dam buoyancy effect (Source: Walder)

4.3 Petrov Lake

Intensive research in Kyrgyzstan is progressing under the auspices of the Department of Physical Geography and Geoecology of Faculty of science of Charles University in Prague. One target of Bohumír Janský´s team is Petrov lake. Petrov lake is proglacial lake located in the west part of Central Tian Shan, in the northwest slope of Ak-Shiirak massif in 3 740 m.a.s.l. under the 23 kilometers long Petrov glacier. Petrov glacier has now about 70 km² and it is retreating quickly. The lake develops in basin of intra-morainic depression after retreat of Petrov glacier. The dam of the Lake contains debris of moraine and ice from the glacier. On the dam, there are also many thermokarst lakes (Janský, 2009).

The first mention about lake observing comes from 1911 when the lake had around 0,2 km². The Lake has always been bigger since that. The fastest growth period was between 1995 and 2006. The lakes growth to the present area of 3.8 km² and maximal depth 21 meters, measured beside calving area of the Petrov glacier (Janský, 2009).

The deciding factor of dam development is the ice in the moraine. The ice melts and subsequently forms the cavity. The process of ice melting is accompanied by moraine´s relief sinking to this cavity. The water is accumulated in the sinks and causes another moraine´s development after that (Janský, 2009).

Next to the Petrov lake there is Kumtor Gold mine. With its height about 4 000 meters above the sea level it is the second highest mine in the world. The current shape of the mine is formed by huge hole in the foothills, deposit of debris, artificial lake and even massive artificial glacier removal technologies for making space for mining (Bary, 2006). Its owner, Canadian company Centerra Gold Inc. make 7,7% of Kyrgyz GDP. More than 2500 employees worked in these extreme conditions. Part of mining technology includes usage of chemicals like sodium cyanide to dissolve gold from granulated ore. Dumps of chemicals and toxic substances are located in goldmine. These facts increase the eventual consequences of lake outburst.

5 Study area

Kyrgyzstan is a large country in central Asia with average altitude of 3 500 meters above the sea level. A large part of the country is covered by Tien Shan and Pamir mountain ranges.

5.1 Discovering

The first map of the area (former western China) was made on order of Chinese emperor in 1708. The mapping was done by Jesuit missionaries Gallerstein, Arora and Espini and the map was published in 1837. Another descriptions and even not good quality map from 1844 was brought by Alexander von Humboldt from his expeditions to the central Asia. Humboldt´s work was refused by Russian scientist Petr Petrovic Semjonov (1827-1914) after his journeys to Tien Shan in the middle of the 19th century. Another expedition to the remote Tien Shan range was accomplished by explorers like Severcov, Fedčenko, Mušketov, Almassy and Prževalskij at the end of 19th century. Since the beginning of the 20th century, central Tien Shan has become more and more interesting in the eyes of the new generation of explorers as well as of alpinists and climbers. Consequences of taken challenges brought discovery of Khan Tengri and Jengish Chokusu (After The Second World War, the peak was renamed to Pik Pobedy, which means Victory Peak) mountains, or first visit of Inylchek Valley. News from Asia excited a German geologist Gottfried Merzbacher too (Vůjta, 1961).

Merzbacher lead the expedition in 1902 to the central Tien Shan with purposeful goals; besides, discover the most outstanding mountain, Khan Tengri - Ghosts King or King of Heaven. After his first unsuccessful attempts to reach the mountain from the north, he focused his effort to the approach from the Inylchek Valley. In autumn 1902 he reached for the first time massive Inylchek Glacier, but he was forced to move back again, to the Chinese side of Tien Shan in order to come back in 1903. With new climbers, the expedition finds themselves again on the Inylchek Glacier. He passed by Inylchek and confirmed the theory about two branches of Inylchek Glacier which we call today South and North Inylchek, and mountain ridge with Khan Tengri in between. At that time, the Italian climber Franz Kostner, member of the expedition, was sent for research farther from the camp, until he reached the lake. It was newly discovered, glacial Merzbacher Lake. It was impossible to cross the lake so later, Merzbacher together with Kostner, continued to the South Inylchek Glacier until they finally reached foot of south face of Chan Tengri (Vůjta, 1961, Merzbacher, 1905).

Merzbacher finally found the truth about Khan Tengri, that it is not a volcano, but marble (that is why it is also called Bloody Mountain) pyramid, probably higher than 7 thousand meters above sea level. For our purposes the discovery of glacier-dammed Merzbacher Lake was more important and it has been now subject of interest for scientist from all around the world (Vůjta, 1961, Merzbacher, 1905).

Another 26 years passed, until another European reached the area again. Russian climber Suchodolskij achieved other side of Merzbacher Lake along its steep banks and proofed Merzbachers theory about path under Knah Tengri from the north. Effort to reach the top of Than Tengri finally culminated in 1931, when three members of Ukrainian expedition, leaded by Michail Pogrebeckij, stood on the summit. Unfortunately for them, in 1943 it was measured by group of Russian surveyors that Jengish Chokusu (Pik Pobedy), is about 440 meters higher than Khan Tengri and it is the highest point of Tien Shan and the second highest mountain in former Soviet Union (Vůjta, 1961).

Here under, there are maps of Central Tien Shan in raw from the older ones of larger scales till the newer ones, of smaller scales (Fig. 9, 10, 11, 12).

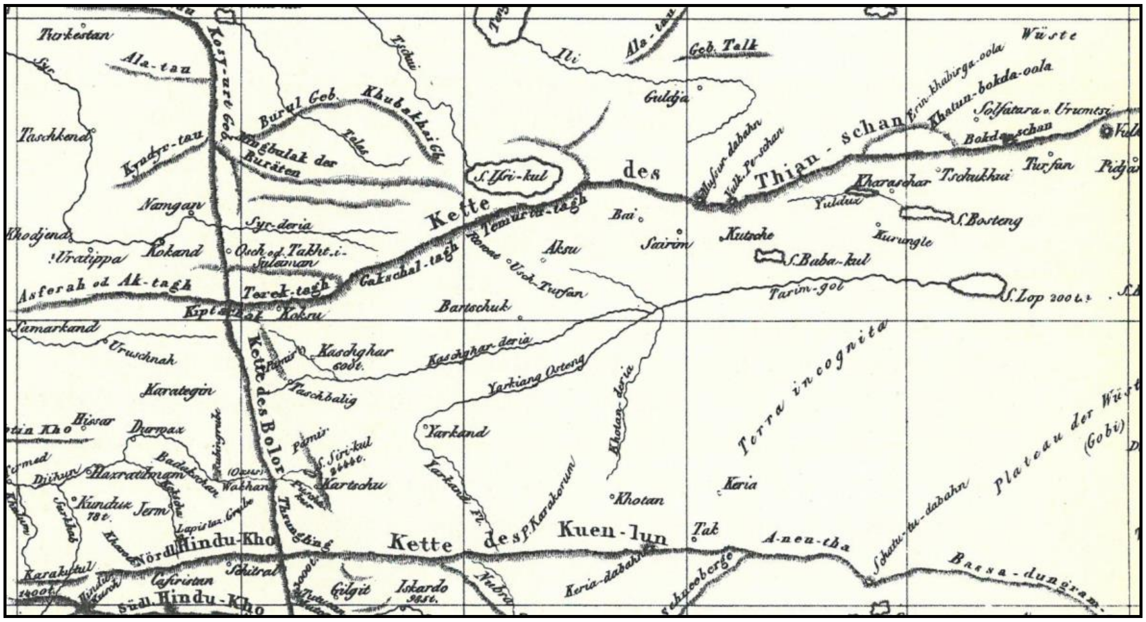


Fig. 9 Map of Tien Shan by Alexander von Humboldt from 1844 - viewport (Source: Vůjta, 1961)

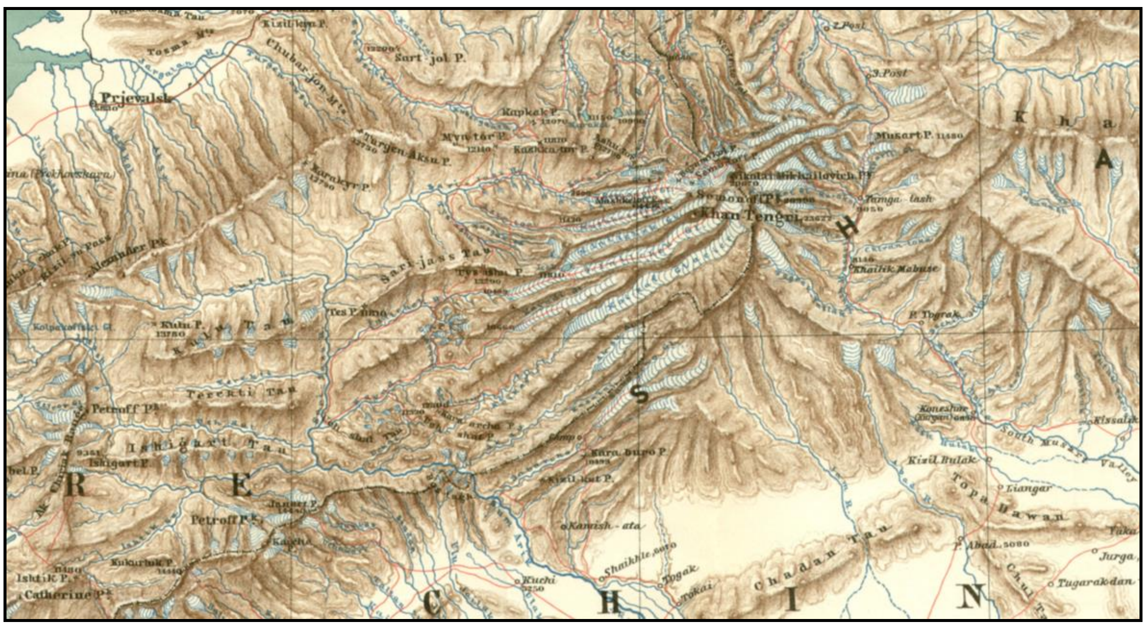


Fig. 10 Map of Central Tien Shan by Gottfried Merzbacher from 1903 - viewport (Source: http://pahar.in/central-asia-after-1900)

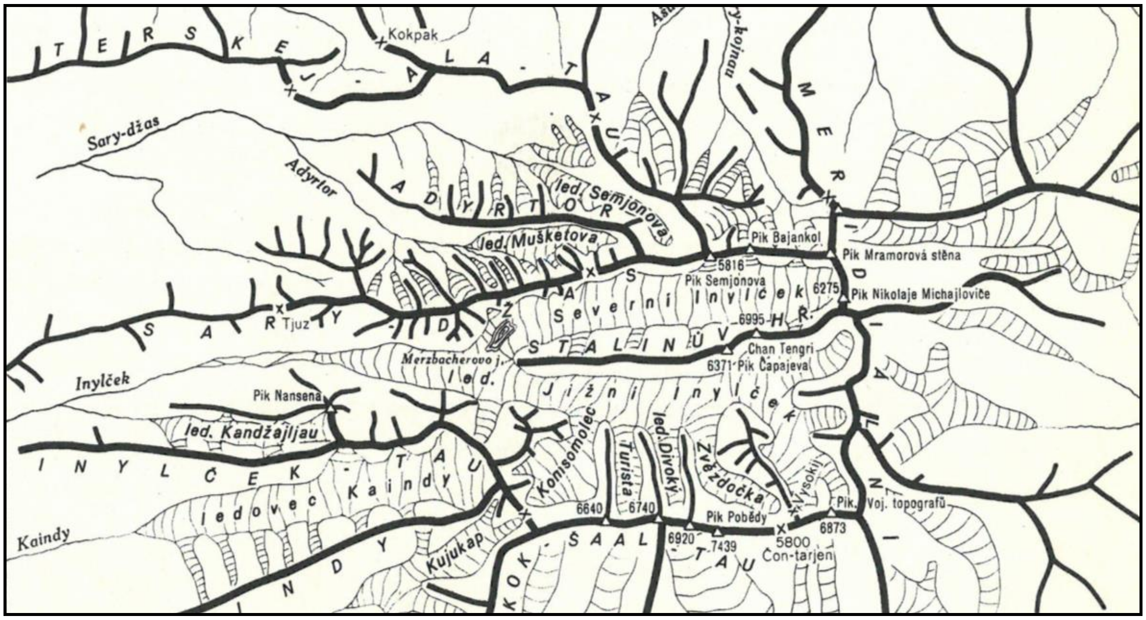


Fig. 11 Map of Central Tien Shan by Vladimír Vůjta from 1959 (Source: Vůjta, 1961)

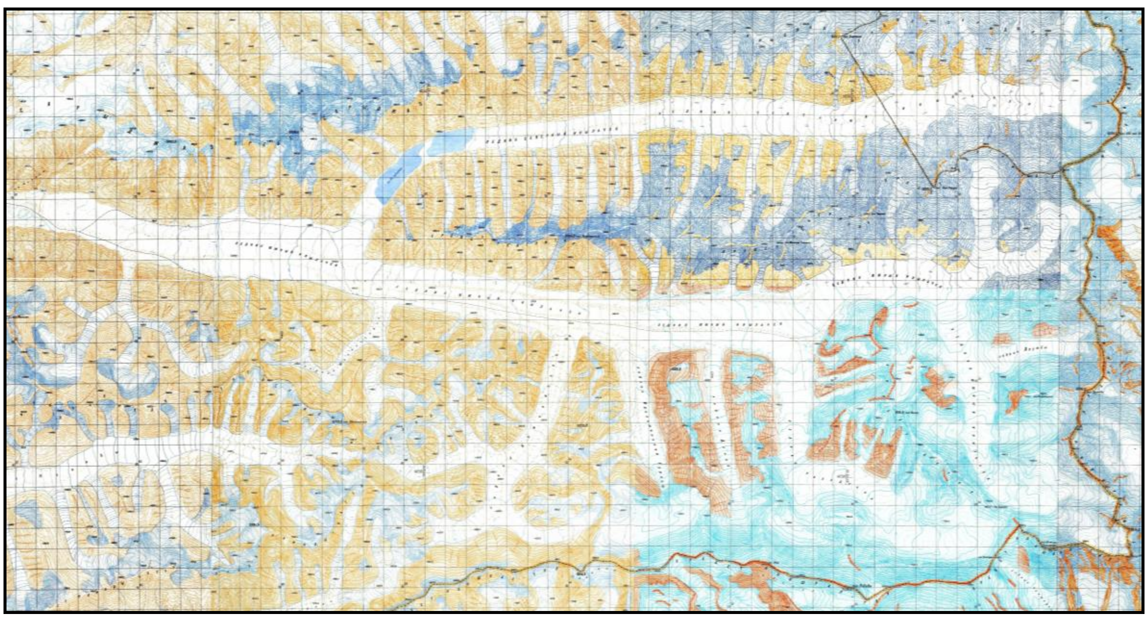


Fig. 12 Soviet Military Map 1:50 000 (Source: http://maps.vlasenko.net/soviet-military-topographic-map/map50k.html)

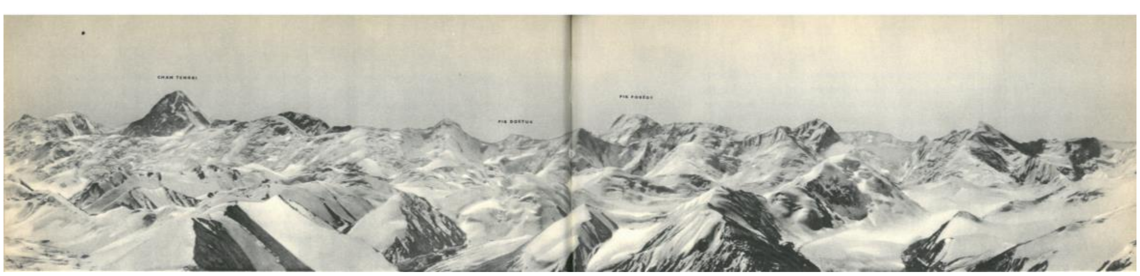


Fig. 13 Panorama of central Tien Shan by Gottfried Merzbacher from north from 1902 (Source: Vůjta, 1961)

Fig. 14, 15 Upper Inylchek Glacier 1959 (Source: Vůjta, 1961)

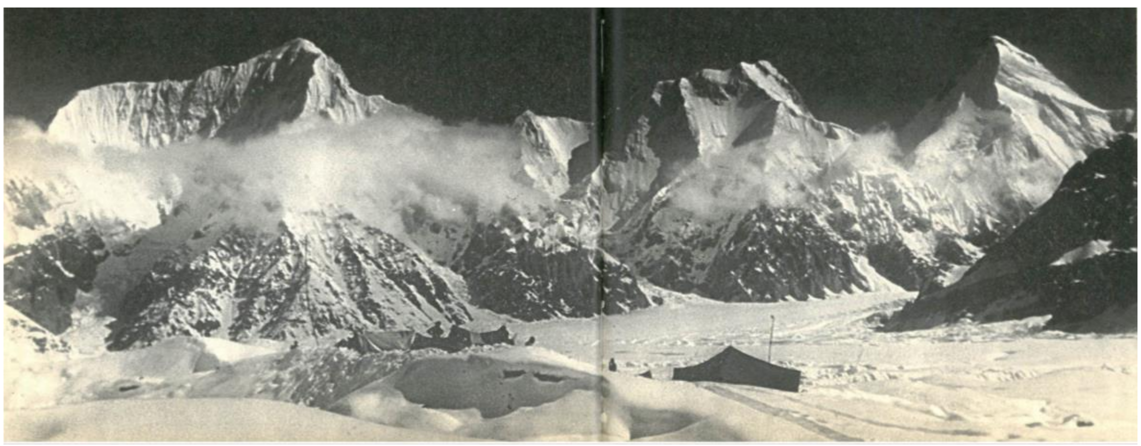


Fig. 16 Chan Tengri from Pik Pobedy Basecamp on Zvezdochka Glacier 1959 (Source: Vůjta, 1961)

The Alpine lakes in Kyrgyzstan are subject to destruction very often and they were described in the past (Janský, 2009; Falátková, 2014; Glazirin, 2010). Since 1952 there have been more than 70 disasters of lakes outburst. Now we know more than 300 lakes which have been potentially dangerous and 12 lakes, which are dangerous (Janský, 2010). One of the biggest proglacial (moraine-dammed) lake threats in Kyrgyzstan is Petrov lake under Petrov Glacier.

5.2 Orography

Tien Shan is one of the largest mountain systems in Asia stretching 2,000 km from west to east between 39° - 46° north and 69° - 95° east (Aizen, 1997). The highest points of Tien Shan are Jengish Chokusu (Pik Pobedy) 7 439 m.a.s.l and Khan Tengri 7 010 m.a.s.l but Its major peaks stand about 4000–6000 m.a.s.l. It is one of the most glaciated mountains in the world. Morphology is typical of young folded mountains with sharp ridges and deep valleys. The range is divided into Central, East, West and North Tien Shan with different climate characteristic (Fig. 17).

5.3 Climate

Very meaningful frame for Tien Shan climate is provided by Vladimir Aizen in his article Climatic and Hydrologic Changes in the Tien Shan, Central Asia: *The main factor determining the climatic regimes is the interaction between the southwestern branch of the Siberian anticyclonic circulation and cyclonic activity from the west.* This definition also sets for the northern Pamir range in south Kyrgyzstan. Central Asia has extremely arid climate, and relatively low precipitation. In spite of that, the range has high concentration of glaciers in mid-altitudes (Aizen, 2006). Higher altitudes of the range are very cold compared to other mountain ranges, because they are located far in the north. It is the northernmost seven thousand high mountain range in the world.

Central Asia has strictly continental climate, which means there are extreme temperatures in the winter and summer (Encyclopedia Britannica) As for the precipitation, the result is 50 mm month^{-1} of precipitation falls during winter and 80 mm month^{-1} precipitation during summer. Most precipitation falls usually around April. Temperatures can be around 30 degrees Celsius in the foothills during the summer. Average winter temperatures are from -4 to -10 in middle altitudes and even more than -20 in alpine regions. Climate diagram is attached down here shows the differences between different parts of Tien Shan in different altitudes (Fig. 17).

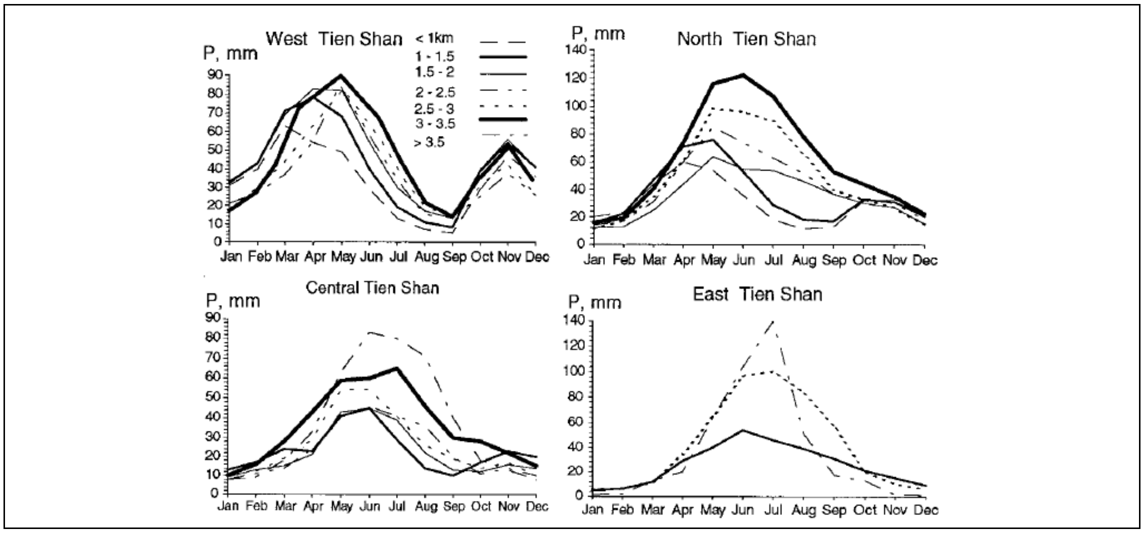


Fig. 17 Precipitation diagrams of different parts of Tien Shan (Source: Aizen, 1997)

5.4 Hydrology

Glaciers of Tien Shan spread in altitudinal belt between 2,800 m.a.s.l. and 7,400 m.a.s.l (Aizen, 2006). Tien Shan glaciated area is major source of water in central Asia. This water of Central Asia endorheic basins feeds the Aralo-Caspian, Balkhash, Issik Kul, and Tarim hydrographic regions. The glaciers of Tien Shan supply water for populations in Kyrgyzstan, Uzbekistan, Kazakhstan, northern Tajikistan, and Xinjiang, China, province (Aizen, 2006).

Gleb E. Glazirin collected data from Inylchek hydrological station in 60´ and 80´ and averaged summer flow of Inylchek River for about 100 m³/sec. The peak flow volume from 1962 - 1965 and 1980 – 1981 in times of Merzbacher Lake outburst are between 800 to 250 m³/sec. Glazirin also estimated the flood height for two outburst events in 1980 for 6 meter, probably equaling for flow 700 m³/sec (Glazirin, 2010).

The flow of Sary Jaz river which Inylchek river is tributary of, is measured in Xiehela hydrological station in China. According to its measurements, the summer flow is around 250 m³/sec and around 150 m³/sec annually. As both rivers are glacier-dependent, its summer runoff increases according glacier development (Kong, 2012).

In context of GLOF of Merzbacher Lake, landscape changes and hydrological regime of the rivers, there is important quote by Gleb E. Glazirin: *The flood plain of the Inylchek River below the Inylchek Glacier has a width up to 1.5 kilometers for a distance of 25-30 kilometers, and caused a significant spreading of the flood wave. Therefore the* *maximum discharge of an outburst from Lake Merzbacher can be assessed as much higher compared to the hydrograph measurement at the Inylchek Mouth gauging station* (Glazirin, 2010).

Over the last 150 years, the glaciers of central Asia have tended to retreat rapidly due to increased temperatures and changes in precipitation partitioning that have caused the glaciers to have mainly negative mass balance, which has also changed river runoff regimes (Aizen, 2006) as well as development of glacial lakes.

5.5 Sary Jaz / Aksu river basin

For our research the Terskey Ala-Too range in Issyk Kul region has been chosen. We decided to set the boarder of our study area same like boarder of Sary Jaz river basin. Sary Jaz flows across the borders between Kyrgyzstan and China to the Tibetan Plato, where the name of the river is Aksu. Our selected area of central Tien Shan is part of Tarim hydrological region (Aizen, 1997). Mountain glaciers in the region are the main source of water for Inylchek and Sary Jaz / Aksu rivers. Glacier-fed streamflow regimes have direct implications on freshwater supply, irrigation and hydropower potential down the stream, especially in China.

The Inylchek Valley is the area that our research is focused on. It is located between east - west oriented Inylchek range and Sary Jaz range. The valley is 150 kilometers long (Vůjta, 1961) and the east part of it is filled by massive Inylchek Glacier. The south oriented slopes are faced to the strong sun and it’s dry and sunny, with less snow and ice cover. The opposite north oriented slopes are shadowy, wet and more glaciated.

Upper part of Inylchek Valley is typical for outwash plain, alluvial cones and fans. Many of perpendicular sub-valleys lead to the main Inylchek Valley. They are small glacier valleys full of snow and ice, which add other material to the main valley. Many of them end with alluvial fans which also feed the river with the sediments. On the slopes above the valley there are smoothed bare rocks extending up to hundreds of meters which come from thousands of years ago, from ice ages.

In the flat and somewhere even 4 kilometers wide bottom of the valley, flows braided Inylchek River. Braiding of the river is typically caused by heavy sediment load, by variable channel depth or variable water discharge. These conditions fit for our area, where the water flow relates with condition up on the glacier and with bursting of Merzbacher Lake. We would like to figure out how is the GLOF of Merzbacher Lake influenced the Inylchek and Sary Jaz / Aksu rivers.

There are two gauging station on the river. One of them is in the Inylchek village, which is located on the west end of the end of Inylchek Valley. The second one, in China, on Aksu river on the south foothills of Tien Shan (Liu, 1992).

Unfortunately, hydrological station in Inylchek was operating only for a total 6 years. Between 1962 and 1965 and again from 1980 to 1981 (Glazirin, 2010). Today the Chinese one, called Xiehela, is around 200 kilometers far from Inylchek Glacier on the stream. Xiehela hydrological station is operating under Xinjiang Hydrological Service since 1956, and it is recording the water volume and flow on the river (Liu, 1992; Kong, 2012).

It was use Google Earth images for the better idea of the shape of the Inylchek Valley (Fig. 18)

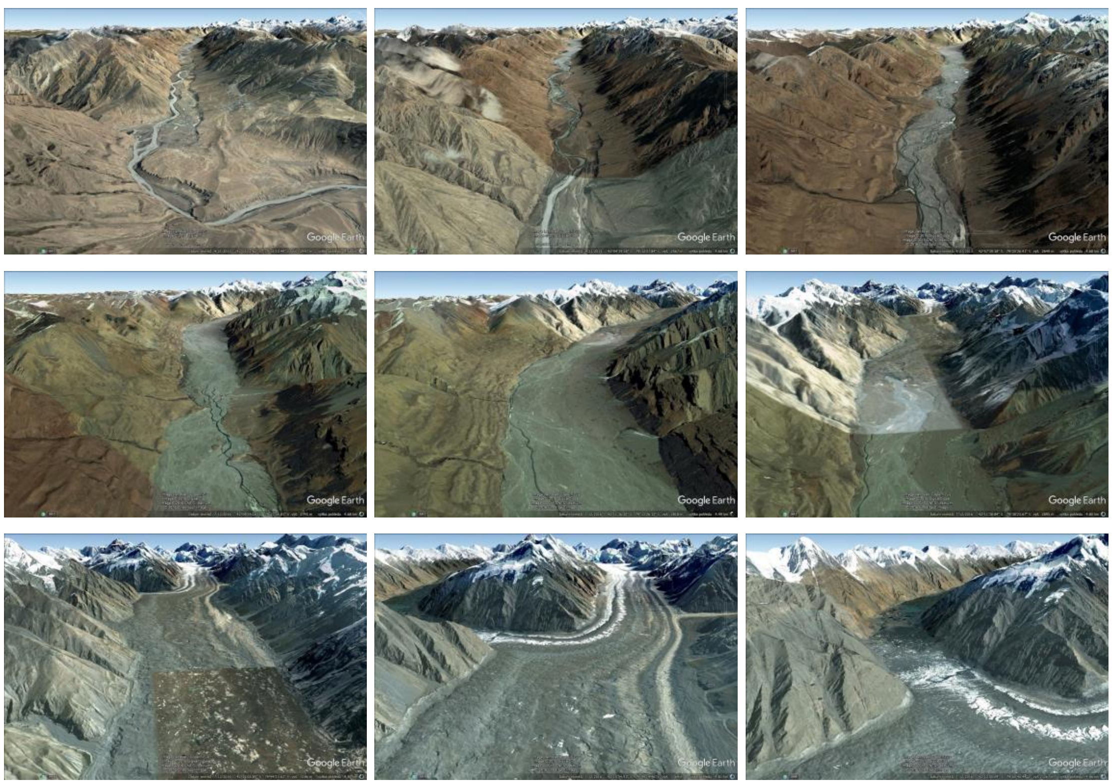


Fig. 18 Inylchek Valley (Source: Google Earth)

According to hydrological potential of Sary Jaz / Aksu river, the working group based on Chinese and Kyrgyz cooperation was established to make investigation about the potential to build hydroelectric power plants on the river.in 2007. The results were presented in article *Water and Hydropower Resources of the Sarydjaz-Kumaryk River and Prospects of Their Use* (Mamatkanov, 2011). The project continues in several scenarios. One of them counts with four water dams: Taldysuu, Enylchek, Akshyirak, Kokshaal with capacities of 210, 840, 480, 600 million cubic meters and total power of 380 MW. The reality is that nowadays, at least one of the dams was already built on the river and filled in 2012.

5.6 Inylchek Glacier

Inylchek Glacier is one of the greatest mountain glaciers in the world. The South Inylchek is with its 59.5 km (Shangguan state length of 60,5 kilometers) the largest Tien Shan glacier located in central Tien Shan, Khan Tengri glacierized massif that covers 4,320 km2 (Aizen, 2006). The glacier itself has 650 km² and in certain parts up to 5 kilometers wide. It is flowing from foots of Khan Tengri and Jengish Chokusu (Pik Pobedy) mountains to Inylchek Valley. Tien Shan is cold place in inland, far away from sea, with lots of snowfall. Northern Inylchek Glacier has been retreated and growth erratically probably because of the influence of Lake Merzbacher. Bigger Southern Inylchek Glacier has been quite stabile despite global warming.

Inylchek has small front moraine, but it has big lateral moraines. In the intersection of Inylchek Glacier with other smaller glaciers, other big moraines are located that keeps material from perpendicular valleys. Surface of Glacier and lateral moraines is dotted with thermokarst lakes. Debris and gravel moved from upper parts of the mountains and big boulders covers the lower part of the glacier.

The Inylchek River flows through the valley and it has almost no riverbed so the water flows irregularly on the surface mostly in form of more streams. The water regime in the valley is changeable, depending on weather, temperature, snowfalls and rainfalls and mainly on the behavior of Lake Merzbacher as mentioned before.

According many investigations of the Inylchek Glacier, its velocity is estimated around 100 meters per year meanwhile the part of glacier stream is directed towards Merzbacher Lake, where its tongue calves. The velocity of that part of the glacier which leads towards Merzbacher Lake is even higher than main stream of the glacier. It is around 120 meters per year. The rest of the South Inylchek has significantly lower velocity (Shangguan, 2014). Especially the last 15 kilometers of the glacier have very low velocity, we can even find there the dead ice areas according to Shangguan. The velocity differences are also proved by GEE Time-lapse analysis, described in chapter 7, Materials and Methods. As the images are presented since 1984 until 2016, we can also observe glacier tongue retreating.

Paradoxical fact was brought by Sangguan. In his work, *Elevation changes of Inylchek Glacier during 1974-2007, Central Tian Shan, Kyrgyzstan derived from remote sensing data,* he mentioned that total area of Inylchek Glacier increased its area about 1,3 km² in period between years 1974 and 2007. Despite of that the tongue of the glacier is retreating. In Sangguan's images we can see glacier velocity from 2002/2003 and 2010/2011 (Fig. 19, 20).

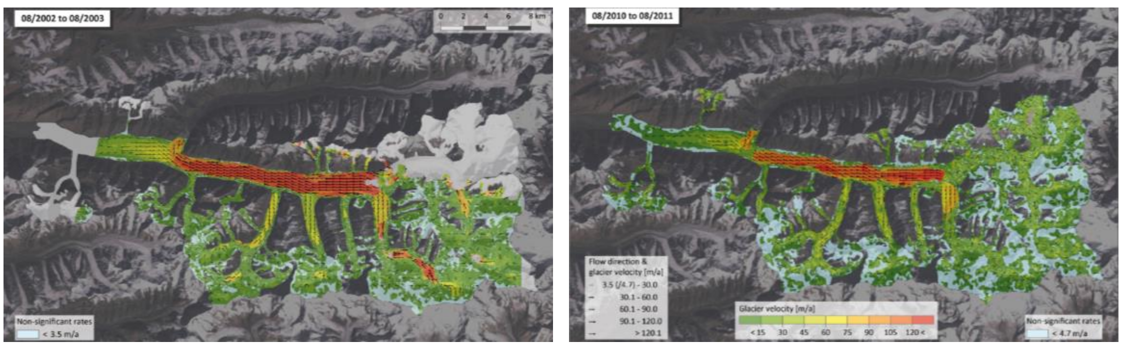


Fig. 19, 20 South Inylchek Glacier velocity in 2008 and 2011 (Source: Sangguan, 2014)

Fig. 21, 22 Inylchek village and junction of Inylchek River and Sary Jaz River, July 2014 (Source: Author)


Fig. 23, 24 Inylchek Valley, July 2014 (Source: Author)


Fig. 25, 26 Head of Inylchek Glacier and Inylchek Valley (Source: Author) / Middle Inylchek Glacier, July 2014 (Source: Author)


Fig. 27 Upper Inylchek Glacier and Khan Tengri (Source: Author) / **Fig. 28** Side moraine of lower part of the glacier with one of the marginal lakes (circa 0,01 km²), July 2014 (Source: Author)

5.7 Lake Merzbacher

Lake Merzbacher is unique glacier dammed lake, which is formed between South Inylchek and North Inylchek glaciers. The lake is filled by meltwater of North Inylchek Glacier. The northern part on South Inylchek Glacier calves here, and adds another floating ice into the lake (in empty lake period). The lake contains the mix of water and ice and the ratio is variable in the summer and in the winter. The lake is divided into two lakes, Lower Lake and Upper Lake. The Lower Lake is periodically bursting out to the south glacier with flow up to 1000 m³/second. The surface of the Lower Lake is usually around 3 km² before outburst (Shabunin, 2012). The flow influenced Inylchek River flows from under the glacier, which is tributary of Sary Jaz (Kyrgyz name) / Aksu (chinese name) river (in the past also known as Kunmalike (Liu, 1992), Kumalak (Kong, 2012), or Kumarik (Rumbaur, 2015) River. The outburst causes severe floods, which can lead to the destruction of infrastructure in the riverbank of Sary Jaz in Kyrgyzstan and Aksu in China (Burmodoi, 2012). The flood period in the Inylchek and Sary Jaz river usually lasts from few days, up to two weeks (Shen, 2009).

The dam is formed by South Inylchek Glacier and it collapses under the water pressure every summer usually. Lake is leaching into the glacier and to Inylchek Valley after that. After the outburst, the South Inylchek Glacier flow velocity increases dramatically to replenish the mass loss caused by calving after the outburst (Li, 2017). The water volume, released from the lake into the glacier after outburst is the main reason for the instability of the riverbed.


Fig. 29 Lake Merzbacher (Source: www.geominprojects.com) / **Fig. 30** Lake Merzbacher before outburst, July 2014 (Source: Author)


Fig. 31 Upper Merzbacher Lake (Source: http://asiamountains.net) / **Fig. 32** Lower Merzbacher Lake before outburst (Source: https://ak-sai.com)

Fig. 33 Lower Merzbacher Lake before outburst, July 2014 (Source: Author)

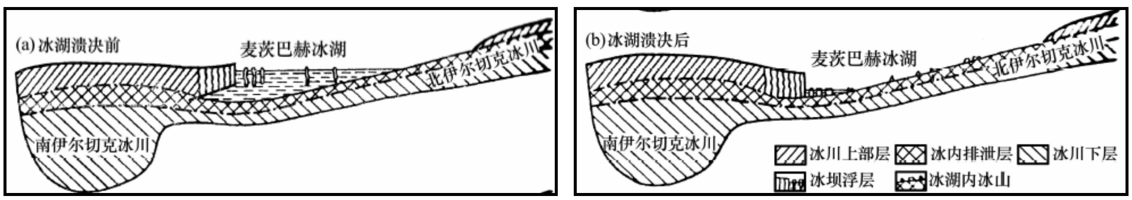


Fig. 34, 35 An ice dam floating before draining of Merzbacher Lake and the profile of the Inylchek Glacier (Source: Shen, 2009)

Fig. 36 Lower Merzbacher Lake before and after outburst (Source: http://gokg.asia/merzbacher-lake)

6 Materials and Methods

6.1 Data collection

To evaluate consequences of GLOF in the chosen area, it is necessary to collect geographic data as mentioned in chapter about Glacier mass balance. We were obliged to choose between remote sensing (aerial photography, satellite imagery) data and ground collection (geodetic). The first option was chosen because it can be easily found online instead of verification in the field.

Satellite imagery can provide us with precise picture of how the landscape has changed in past 40 years. For effective description of landscape changes, we used remote sensing data. Some of that data were processed in GIS software ArcMap 10.2 and CAD software Microstation V8. For browsing the raster images and data format exchanging the Adobe photoshop CS5 was used. The main source of satellite images was provided by NASA and USGS program Landsat.

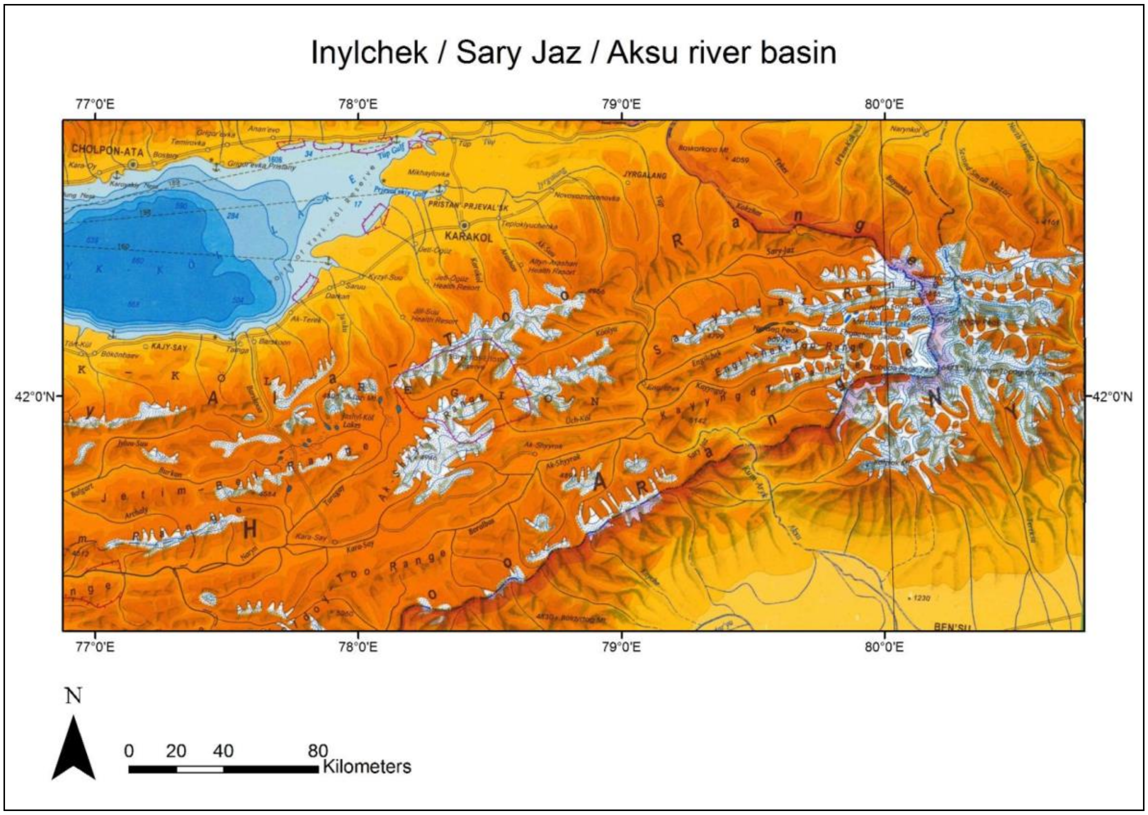


Fig. 37 Geographical map of Kyrgyz Republic (Source: Goskartografia)

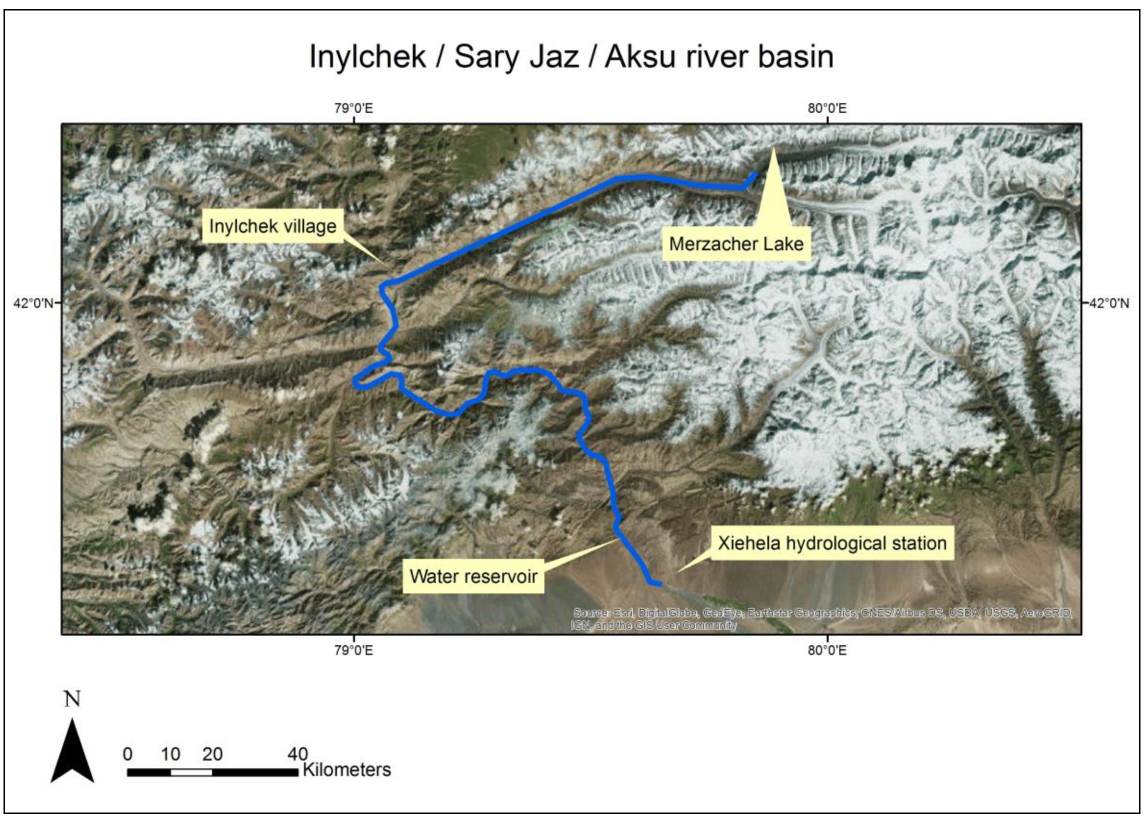


Fig. 38 Situation of study area

6.2 Digital Elevation Model

For better understanding of the Inylcheck Valley shape, it was used elevation representation with help of profiles. The digital elevation model (DEM) SRTM 1, acquired by Sentinel satellite in 2014, served as input data for cross sections creating. It was made of 4 transverse cross sections and one longitudinal profile of Inylchek Valley. The shape and width of Inylchek Valleys bottom are obvious from the cross section which can provide us of resolution of 30 meters to pixel. Each cross section is 10 kilometers wide and the longitudinal profile has even 120 kilometers from the end of North Inylchek Glacier to Inylchek village. On the cross sections A-A´ and B-B´, we can observe the development of the river basin. On the cross section B-B´ we can see braided river on wide flat plain with no significant river basin. On the cross section A-A´ we can see the sharp valley with solid river basin. On the cross section C-C´, going through lower part of Inylchek we can clearly see the width of the valley, which is more than 4 kilometers, and concave shape of the glacier surface. Cross section D-D´ goes through Merzbacher Lake. As the date of acquisition of DEM is September 2014, the Lake was probably after outburst. The cross section D-D´ proves that, because there is the low elevated river basin on the north side of the bottom of the lake. This river basin is shaped by stream flowing from the Upper Merzbacher Lake when the Lower Merzbacher Lake is empty. Longitudinal profile shows the steep tongue of North Inylchek Glacier, the bottom of Upper Lake and bottom of Lower Lake. Bigger Lower Lake ends by significant wall of South Inylchek Glacier. The wall of ice is dozens of meters high and it usually calve to the Lake during the period of bursting. Then the cracked and relatively (compared to the slope of the valley) steep South Inylchek Glacier is shown on the longitudinal profile. The steepness of the Glacier surface is caused also by its thinning from the upper parts to the lower parts towards its tongue.

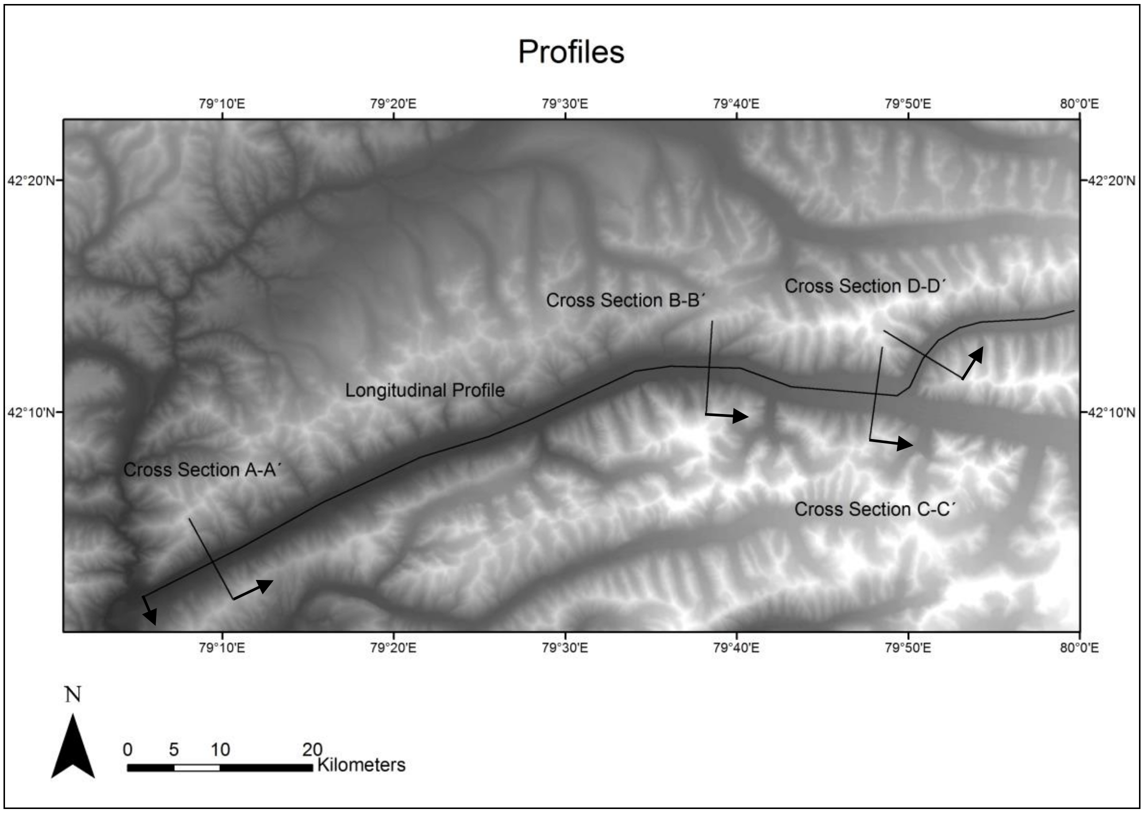


Fig. 39 Cross sections and longitudinal profile situation

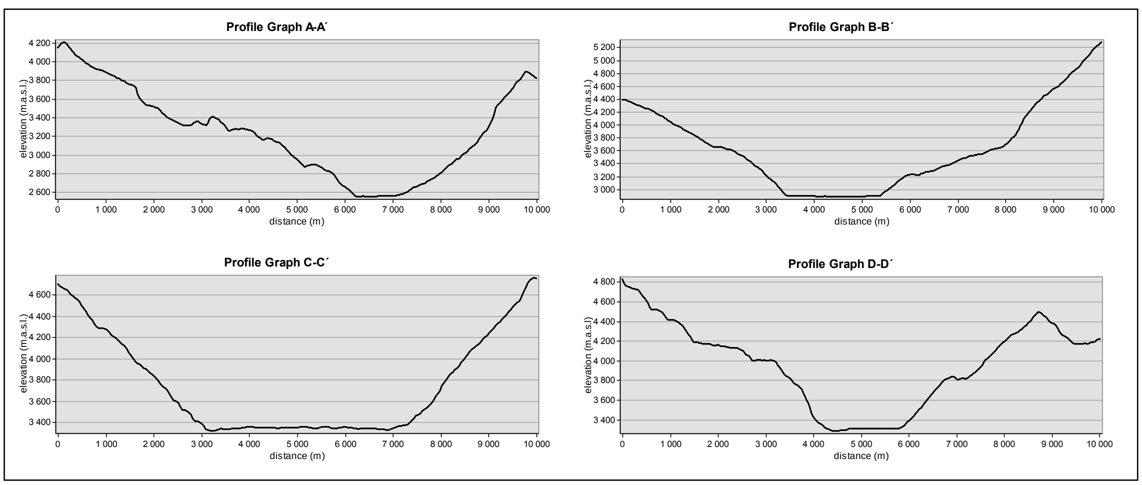


Fig. 40 Cross sections

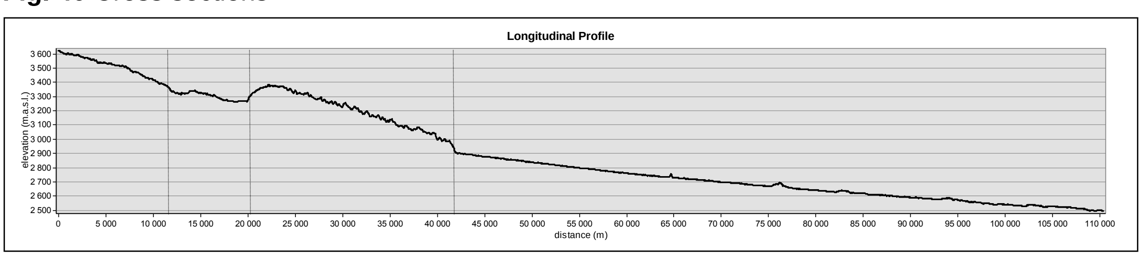


Fig. 41 Longitudinal Profile

6.3 Landsat

The analysis of Landsat data allowed us to document various phases of the outburst cycle. Landsat satellites take satellite images of planet Earth since 1972. It was revolutionary technological progress for observing Earth surface. 8 Landsat satellites were released to the orbit until now meanwhile older satellites were gradually replaced by the new ones (figure 42). The data has wide scale of use, from mapping the surface, monitoring of forests or crops, to landscape changes etc. Landsat are also main source of data for making GEE Time-lapse images.

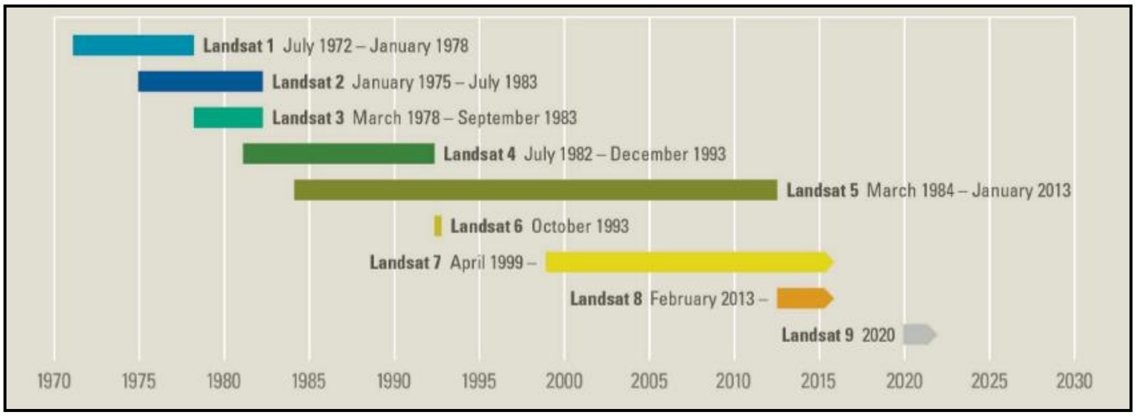


Fig. 42 Timetable of Landsat satellites operations (Source: https://landsat.usgs.gov/)

The black gaps occurred in chosen images from Landsat 7 (chapter 8, Results). It is the consequence of Scan Line Corrector (SLC) failure, which compensates the forward motion of the satellite. Unfunctional SLC causes that Enhanced Thematic Mapper Plus (ETM+) sensor of the satellite does not work properly (does not follow satellite ground track) and makes the black gaps. Despite the incident that happened in 2003, Landsat 7 ETM+ is still capable of acquiring useful image data (this thesis proving it) with the SLC turned off - it is still operating in "SLC-off" mode.

The SLC-off effects are the most obvious along the edge of the scene and gradually diminish towards the center as shows figure 43. Our images point out the axis of satellite ground footstep farther to the east, as obvious from figures.

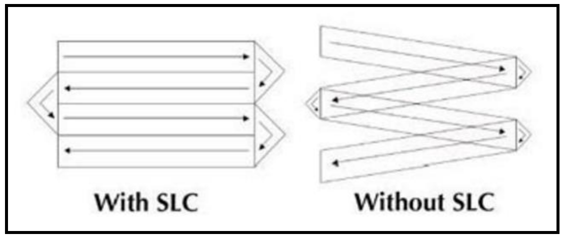


Fig. 43 Schematic representation of consequences of the "SLC-off" mode of acquiring data (Source: https://landsat.usgs.gov/slc-products-background)

6.4 Google Earth Engine

This open platform is a strong tool for observing landscape changes all over the world. It provides datasets of satellite images since 1984 till today. Google Earth Engine stores satellite imagery, organizes it, and makes it available for the first time for global-scale data mining. The public data archive includes historical earth imagery going back more than forty years, and new imagery is collected every day.

The tool was already used in fields of Global Forest Cover Change or Habitat Monitoring researches (Hansen, 2013).

As GEE works as satellite images browser and library, it provides also time-lapse images in web browser. We can observe quickly landscape changes. For our purpose, it was used for pre-research of landscape changes of given area. GEE has other platforms such as Google Earth Engine Explorer (GEEE). GEEE provide us NDWI data about the area, as shown later the figures 54 and 55.

7 Results

To evaluate landscape changes between and after the outburst, it was necessary to get dates of the outbursts. The time series was chosen from 1970 until 2008 (last recorded and described outburst). We chose the desired data from researchers of Glazirin 2010, Kingslake 2013, Burmodoi 2012, Ng 2009 and Liu 1992. Some of their sources show also peak released water volume of the flood, measured at Xiehela hydrological station in China, after related outburst date. For some outburst dates, the measured data was missing, so the flood volume was estimated, or reconstructed by using hydrological models. In attached table on figure 44, the chosen data are listed. There is a graph of frequency of outbursts between 1970 and 2008 in figure 45. We can see the decreasing trend of lake outbursts dates in the graph.

The measured volumes of released water are typically from 0,86 x $10^8 m^3$ (in 1970) to 2,84 x $10^8 m^3$ (in 1996). We chose four outbursts with big measured released water volume and with most reliable sources from 1996, 2002, 2006 and 2008.

Year of outburst	Date of outburst (Glazirin, 2010)	Date of flood peak (Kinglsake, 2013)	Date of outburst (approximately)	Measured flood volume $10^{6} m^{3}$	Date of outburst (Bormodol, 2012)	Date of flood peak (Ng, 2009)	Date of outburst (approximately)	Measured flood volume $10^{6} m^{3}$	Month of outburst (Liu, 1992)	Date of outburst (approximately)	Measured flood volume (estimated) $10^{6} m^{3}$
1970	1.9.1970	31.7.1970	26.7.1970	0,86		31.7.1970	26.7.1970	0,86	31.7.1970	26.7.1970	1,14
1971		17.8.1971	12.8.1971	1,33		17.8.1971	12.8.1971	1,33	17.8.1971	12.8.1971	1,55
1972		4.10.1972	30.9.1972	1,61		4.10.1972	30.9.1972	1,61	4.10.1972	30.9.1972	1,60
1973		2.9.1973	28.8.1973			2.9.1973	28.8.1973		2.9.1973	28.8.1973	2,27
1974		8.8.1974	3.8.1974			8.8.1974	3.8.1974		8.8.1974	3.8.1974	0,98
1975		12.9.1975	7.9.1975			12.9.1975	7.9.1975		12.9.1975	7.9.1975	0,38
1976		24.8.1976	19.8.1976	1,31		24.8.1976	19.8.1976	1,31	24.8.1976	19.8.1976	1,66
1977											
1978	5.9.1978	24.5.1978	19.5.1978	2,51		24.5.1978	19.5.1978	2,51	24.5.1978	19.5.1978	3,08
		9.8.1978	4.8.1978			9.8.1978	4.8.1978		8.8.1978	3.8.1978	0,50
1979											
1980	15.5.1980	27.5.1980	22.5.1980	2,36		27.5.1980	22.5.1980	2,36	27.5.1980	22.5.1980	3,27
	2.9.1980	12.9.1980	7.9.1980	1,51		12.9.1980	7.9.1980	1,51	12.9.1980	7.9.1980	1,51
1981	8.7.1981	15.7.1981	10.7.1981		8.7.1981	15.7.1981	10.7.1981		15.7.1981	10.7.1981	0,94
	8.8.1981				8.8.1981						
1982	14.8.1982	21.8.1982	16.8.1982	1,74		21.8.1982	16.8.1982	1,74	21.8.1982	16.8.1982	1,61
1983		22.8.1983	17.8.1983			22.8.1983	17.8.1983		22.8.1983	17.8.1983	1,76
1984	20.8.1984	26.8.1973	21.8.1973			26.8.1984	21.8.1973		26.8.1984	21.8.1973	1,40
1985	9.8.1985	15.8.1985	10.8.1985			15.8.1986	10.8.1985		15.8.1985	10.8.1985	1,91
1986	26.8.1986	1.8.1986	27.7.1986			1.8.1986	27.7.1986		1.8.1986	27.7.1986	2,72
1987	14.8.1987	19.8.1987	14.8.1987			19.8.1987	14.8.1987		19.8.1987	14.8.1987	2,25
1988		12.12.1988	7.12.1988	2,10		12.12.1988	7.12.1988	2,10	12.12.1988	7.12.1988	2,07
1989	10.10.1989	31.8.1989	26.8.1989	1,28		31.8.1989	26.8.1989	1,28			
1990	5.8.1990	10.8.1990	5.8.1990		5.8.1990	10.8.1990	5.8.1990				
1991		24.7.1991	19.7.1991			24.7.1991	19.7.1991				
1992		4.8.1992	30.7.1992			4.8.1992	30.7.1992				
1993		22.8.1993	17.8.1993			22.8.1993	17.8.1993				
1994		24.7.1994	19.7.1994			24.7.1994	19.7.1994				
1995		18.7.1995	13.7.1995			18.7.1995	13.7.1995				
1996		5.12.1996	30.11.1996	2,84		5.12.1996	30.11.1996	2,84			
1997		31.7.1997	26.7.1997	1,29 (recon)		31.7.1997	26.7.1997				
1998		27.7.1998	22.7.1998	1,26 (recon)		27.7.1998	22.7.1998				
1999		19.7.1999	14.7.1999	1,74 (recon)		19.7.1999	14.7.1999				
2000		27.7.2000	22.7.2000	1,72 (recon)		27.7.2000	22.7.2000				
2001	27.7.2001	31.7.2001	26.7.2001	2,04 (recon)		31.7.2001	26.7.2001				
2002	1.8.2002	6.8.2002	1.8.2002	1,83 (recon)	1.8.2002	6.8.2002	1.8.2002				
2003	22.7.2003	26.7.2003	21.7.2003	1,54 (recon)	22.7.2003	26.7.2003	21.7.2003				
2004	6.8.2004	9.8.2004	4.8.2004	1,95 (recon)		9.8.2004	4.8.2004				
2005	14.7.2005	15.7.2005	10.7.2005	1,52 (recon)		15.7:2005	10.7.2005				
2006		30.7.2006	25.7.2006	2,10 (recon)							
2007		11.7.2007	6.7.2007	1,89 (recon)							
2008		15.7.2008	10.7.2008	2,07 (recon)							

Fig. 44 Table of frequency of outbursts between 1970 until 2008 and flood volumes in m^3 per day (Source: Glazirin 2010, Kingslake 2013, Burmodoi 2012, Ng 2009, Liu 1992)

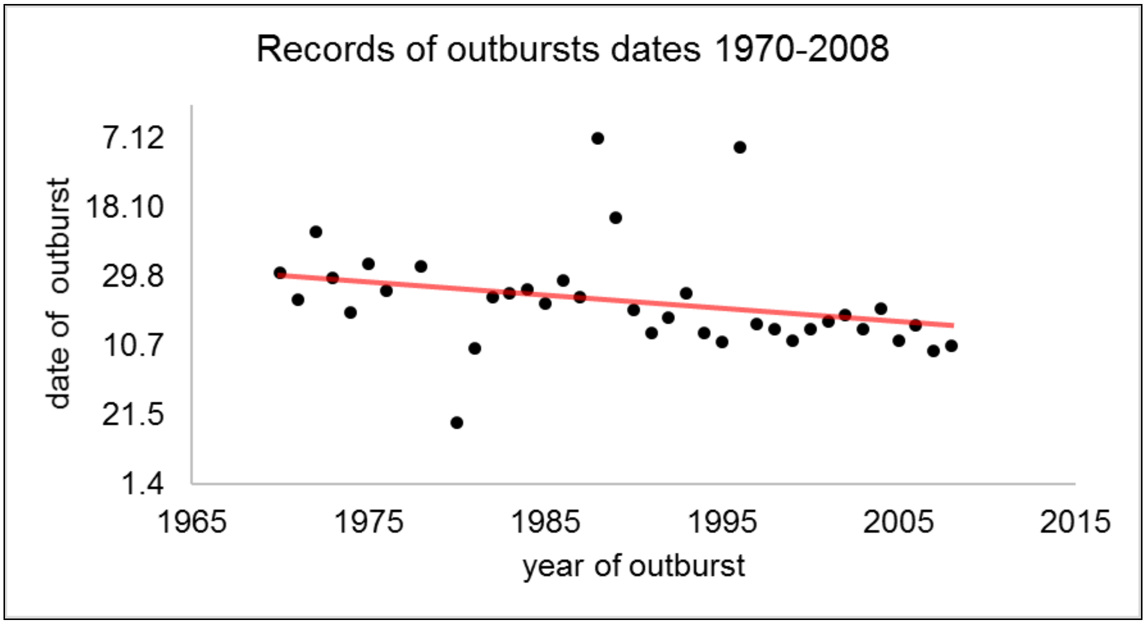


Fig. 45 Graph with trend of outbursts dates 1970-2008

The best quality of images for our purposes was provided by Landsat 5 for outburst in 1996 and Landsat 7 for outbursts in 2002, 2006 and 2008. All images are in natural color spectrum. We chose wanted datasets for period before and after outburst and we compared them. Usually the images were taken from few days to few weeks before or after outburst, depending on availability of the data.

7.1 Changes of Merzbacher lake derived from satellite data

We focused on the specific and most changeable parts of our area. Merzbacher Lake itself is one of them and we focused on it in the first part of our results. In the images of Merzbacher Lake there are some significant changes of the surface before and after outburst. There is smooth surface of water (dark blue) or ice (light blue) in the lake in figures 46-49. After the event, no water occurs on the site, only the dead ice flowed on the surface is settled on the bottom of the empty lake. Meanwhile significant changes of Lower Merzbacher Lake occur, the Upper Merzbacher Lake does not show any modifications. There are just little position and shape changes of stream basin between Upper Lake and empty Lower Lake after each outburst. According to our research about ice dam buoyancy effect, changes also occur on the ice dam formed by that part of South Inylchek Glacier flowing towards Merzbacher Lake. When the water flows out from the lake into the glacier, the ice dam has no support in the water pressure and it calves and settles down. It is proved by the new crevasses farther from the ice dam on the glacier. Another area showing the landscape after outburst is upper part of Inylchek Valley. The released water volume flowing from the glacier tongue has big influence on the shape of the valley, especially in its upper, flat and wide parts where the river braided heavily. The Landsat images show the shape changes of Inylchek River basin and their quantity.

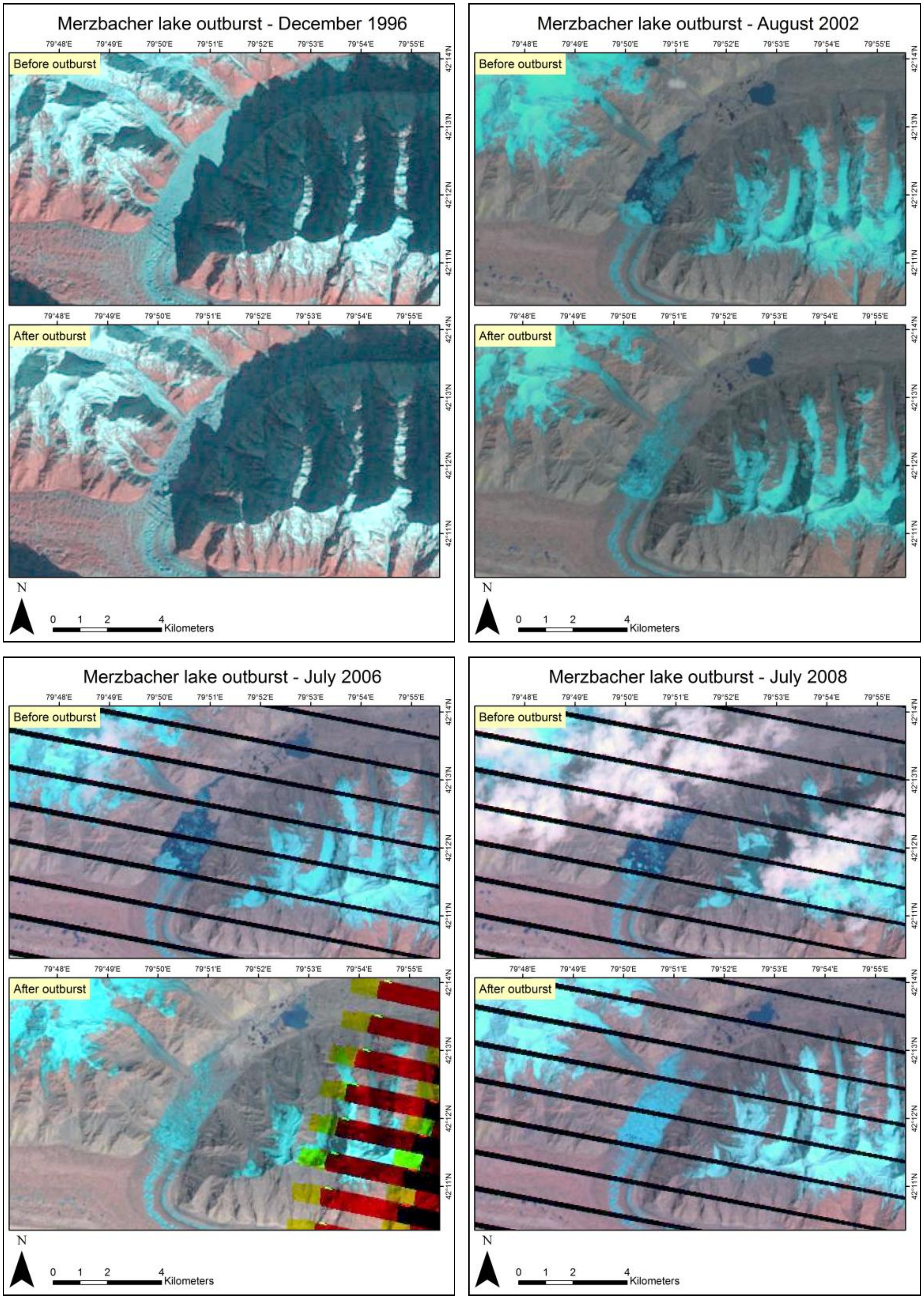


Fig. 46, 47, 48, 49 Merzbacher Lake Landsat images comparison

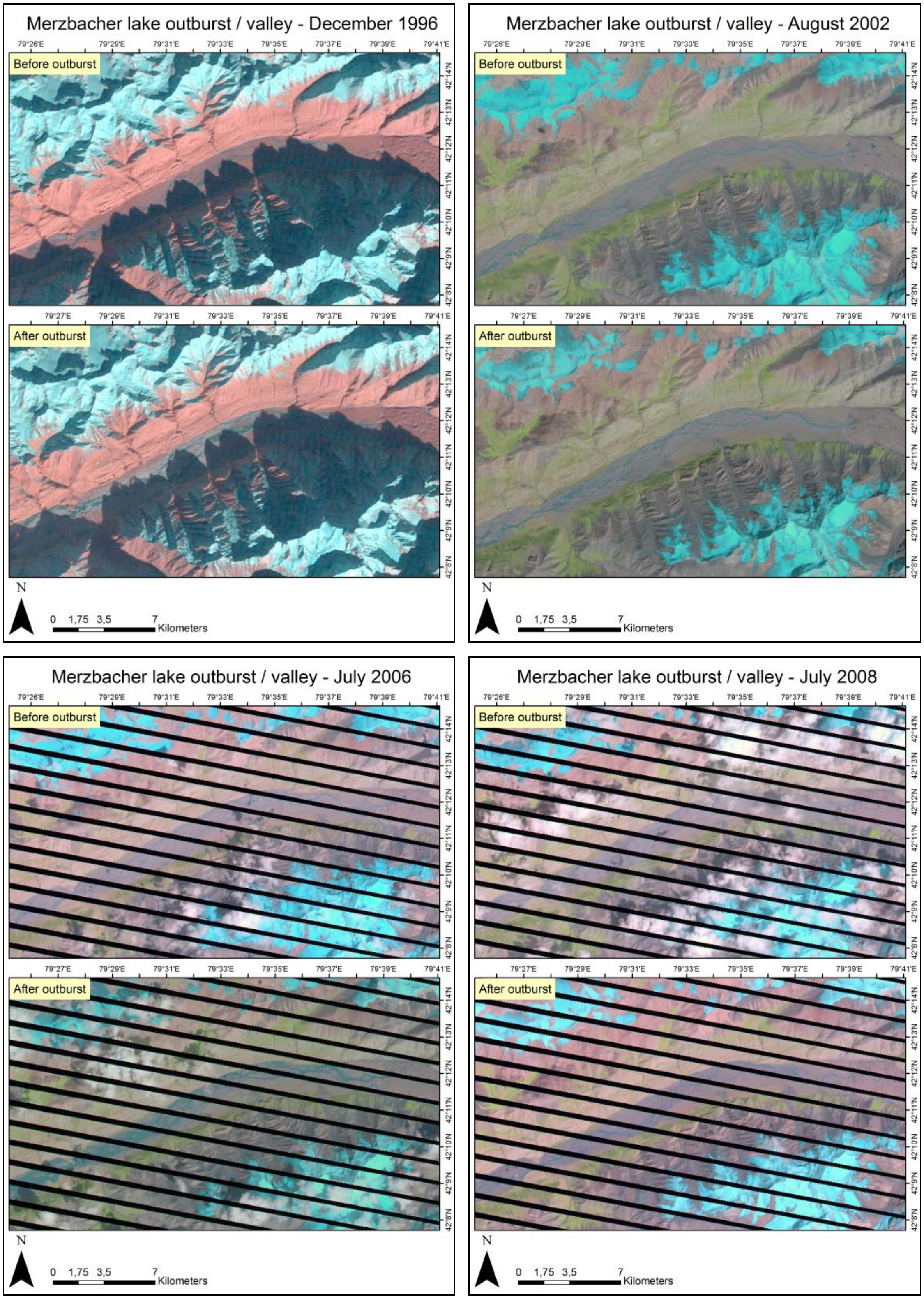


Fig. 50, 51, 52, 53 Inylchek Valley Landsat images comparison

7.2 Normalized Difference Water Index

For better description of that area we chose different data. The source data for 2008 outburst and its consequences was provided by Ladnsat 7 satelite again, but Normalized Difference Water Index (NDWI) was used. This index was developed for better analysis of water occurrence based by remote sensing. We used processed Landsat 7 32-Day and 8-Day NDWI composite form GEEE. It means the combination of pictures taken in period of 8 or 32 days. Just two shades for the map results was chosen. The red one for snow, ice and representation and the green one for everything else. Our NDWI data was chosen as follows:

- 8-Day composite: Jun 25, 2008 - Jul 3, 2008 / Jul 27, 2008 - Aug 4, 2008
- 32-Days composite: Jun 9, 2008 - Jul 11, 2008 / Jul 11, 2008 - Aug 12, 2008

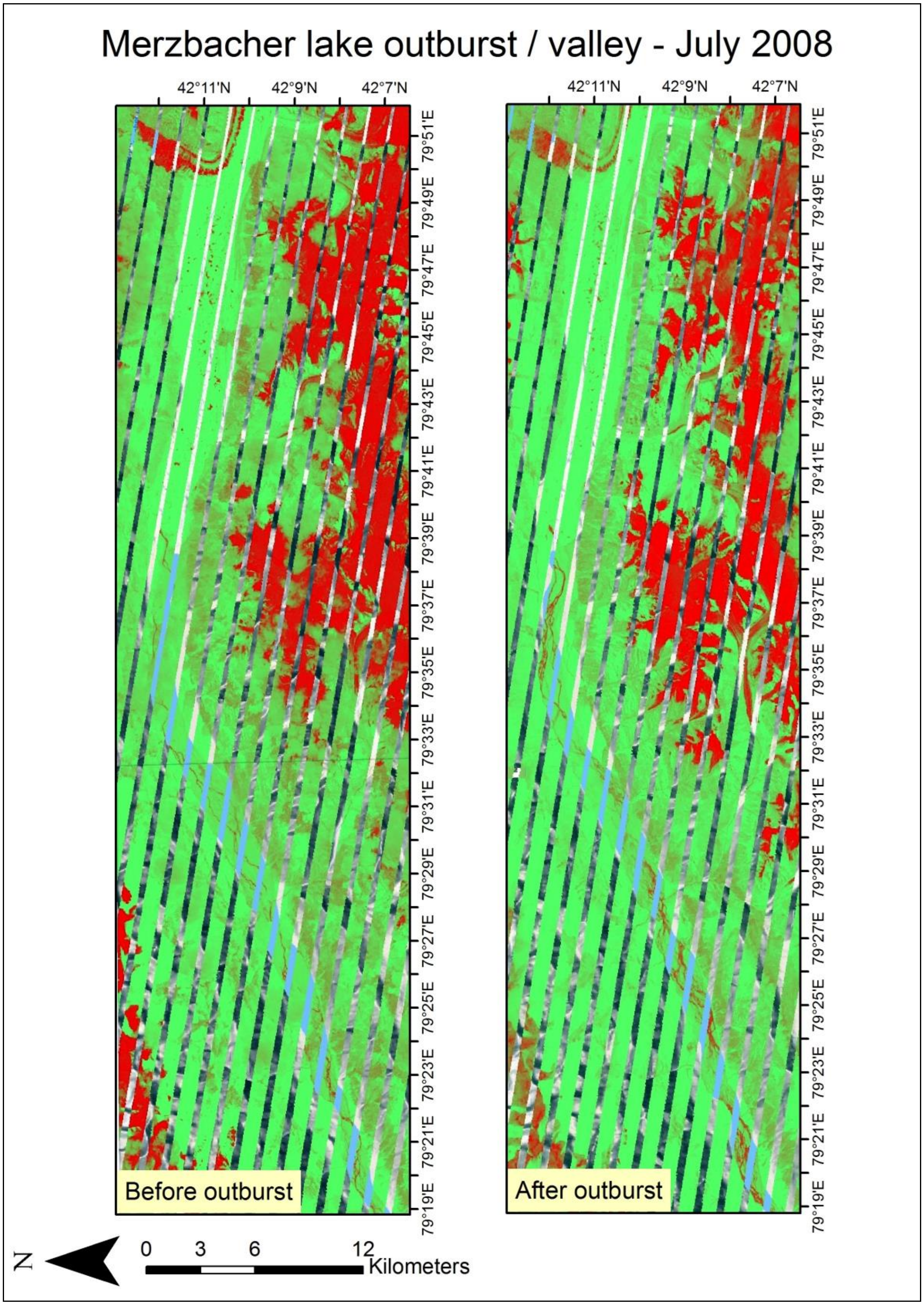


Fig. 54 Ladnsat 7 NDWI 8 days collection images comparison

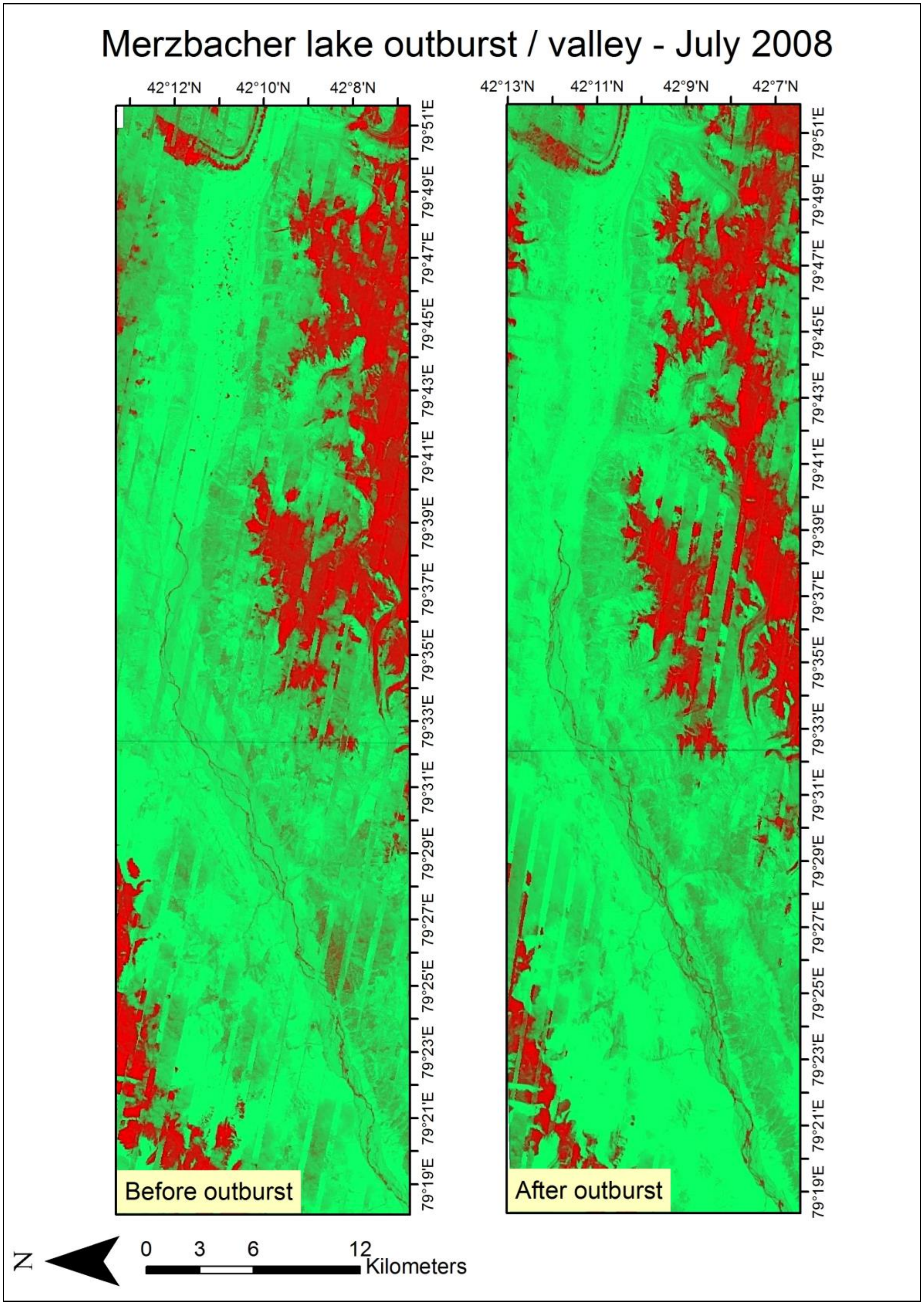


Fig. 55 Ladnsat 7 NDWI 32 days collection images comparison

7.3 South Inylchek Glacier velocity

To evaluate South Inylchek Glacier velocity the GEE Time-lapse tool was used. The 26 picture from GEE Time-lapse was chosen. The images were taken annually from 1990 until 2016. In the figure 56, there is a raw of the images with additional vector descriptions such as: glacier stream direction, glacier tongue changes, and three points. The points represent specific place on the glacier surface, which is moving with glacier. It is evident, that velocity of the upper parts of the glacier is much higher (around 150 meter per year) than the lower parts of the glacier. Last 10 kilometers of the glacier is in bad condition. The consequences of low velocity and dead ice inside caused thinning of this part of glacier. That is obvious on the side parts of the lower parts of the glacier. There is a proof of Inylchek Glacier flow velocity in the annotations of the figures.

Fig. 56 Time series of images 1990 - 2016

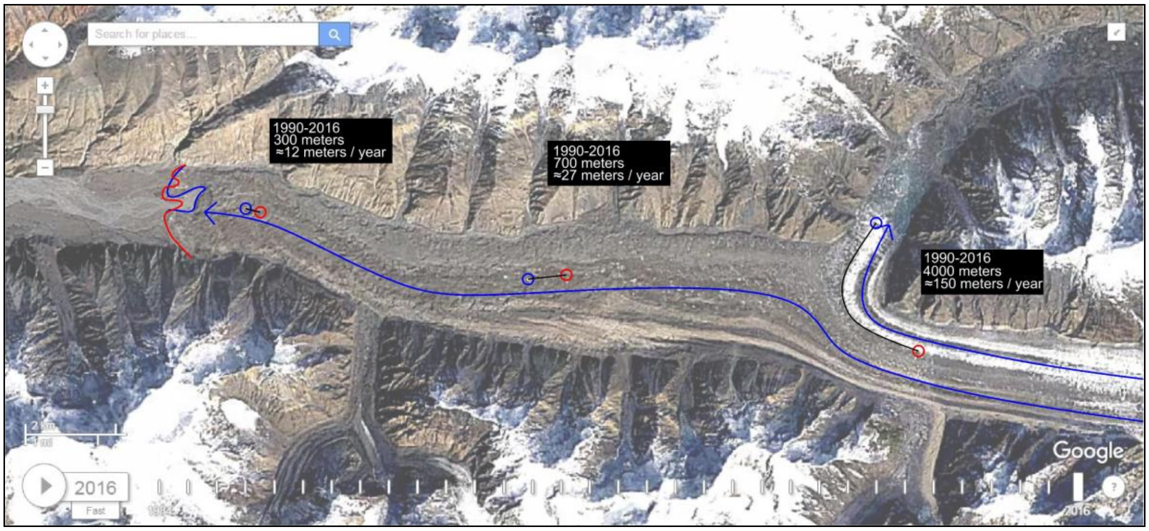


Fig. 57 Inylchek Glacier velocity

8 Discussion

The information about Merzbacher Lake outburst were collected since 1970 (Fig. 44 Table of frequency of outbursts between 1970 and 2008 and flood volumes in m³ per day). The data were found inaccurate in outburst events because the data come from different sources. The outburst dates and flood peak volume differ according to different sources. The outburst dates are usually obtained from flood peak volume, which is measured at Xiehela station several days after the event. Some of the newer data were not measured, but only obtained from remote sensing data from last few years (after construction of Chinese water reservoir). Some older data were given only by eye witnesses. The trend of the annual outburst dates is obvious in figure 45 (Graph with trend of outbursts dates 1970-2008). Despite the inaccuracy of some data, the trend is identical to other articles (Glazirin, 2010, Kingslake, 2013).

The flood volumes measured on Inylchek hydrological station during its operation (1963 - 1966 and 1980 - 1981) were compared with the same period of measuring on Xiehela hydrological station in China. As the Inylchek hydrological station measured only discharge on Inylchek River circa 70 kilometers far from the Merzbacher Lake, the Xiehela measured much higher flow of Sary Jaz / Aksu river with all its tributaries around 200 kilometers far from the Lake. The result of measured flow was approximately from two to three times higher on Xiehela hydrological station. The relatively small ratio between measured flow according to catchment area of the rivers just prove the importance of Central Tien Shan glaciated area and Inylchek Glacier itself.

Some problems occurred during the evaluation of the satellite images. As the floating ice is present on the lake surface before outburst, that can occur on the lake bottom after the outburst. It is paradoxically easier to describe the Merzbacher Lake in Landsat images in normal color spectrum outburst than images which use NDWI index.

Construction of the new water reservoir started in 2010 in Chinese part of the river. According to the GEE Time-lapse, it was filled in 2012. The dam is located just in the area where the Aksu river flows from the Tien Shan mountains into the Taklamakan Desert. It is probably the result of the part of the hydropower project described in *Water and Hydropower Resources of the Sarydjaz-Kumaryk River and Prospects of Their Use* study. No relation between Merzbacher Lake outburst and water volume in the Chinese water reservoir was found. Releasing of the reservoir occurs usually in period of weeks according to satellite imagery. It is clearly visible from the upper part of the reservoir, where the edge between water surface and reservoir bottom is changing. Unfortunately, its influence on the flood from Merzbacher Lake is not evident from the images. Another problem for detecting the flood in the reservoir is the low quality of the satellite images. Resolution usually 30 meters per pixel for Landsat cannot provide proper information about the reservoir surface. Another reason for the impossible detection of the flood from our data is that the flood spread on the Sary Jaz river on the way towards the reservoir. The 200 kilometers’ distance from the Merzbacher Lake to the reservoir provides space and time for that spread.

9 Conclusion

This chapter is just a general overview of the landscape development under glacier lakes in Tian Shan and Sary Jaz / Aksu river basin. It´s important to understand the natural hazards which come with that process. Land surface changes here are the consequences of lots of factors like weather, water regime and erosion. It´s important to describe this process and to protect these rare landscape natural and urban areas in valleys. Kyrgyzstan is quite stable and accessible country for research teams from all over the world.

During the work on this thesis, we encountered following potential topics for future researchers. One of the topic could evaluate differences between runoff volume of water from that part of Inylchek Glacier leading towards Merzbacher Lake, and runoff volume from main stream of Inylchek Glacier leading to the Inylcheck Valley. It would be useful to focus on the prediction of the Merzbacher Lake outbursts. It will be needed especially for the next steps of the hydropower development project. It would be also important to develop these research, which combine the remote sensing data and hydrological modeling.

The strong connection was found between Merzbacher Lake outburst and braiding of the Inylchek River. The shape of the valley bottom is given by periodical GLOFs of the Lake. Since 1970 no GLOF strong enough to change the valley significantly was recorded. For example, flood which could flush the alluvial fans in the valley, or destroy the higher elevated banks along the river. Gleb E. Glazirin encountered the GLOF influence to the valley (Glazirin, 2010). We found that even the flood wave with 600 centimeters of height (for flood volume of 700 m^3/sec), have no significant evidence in the valley landscape. There are some landforms in the valley, which prove significantly different behaving of the Inylchek Glacier and Inylchek river. It is especially high alluvial fans, steep banks, sedimentation areas, glacier trim line etc. This whole landform could be tens of thousands of years old and probably older that Merzbacher Lake itself and its outbursts (Merzbacher, 1902).

The selected data cannot provide us information about following landscape consequences in Sary Jaz / Aksu river bad, from tributary with Inylchek River to Chinese water reservoir. The valley is too sharp and slopes are too steep for assessment of the landscape changes in that area. This is also a reason why the destructive consequences for infrastructure in some areas cannot be compared (Shabunin, 2012). The water reservoir serves as a protection against some negative influence of GLOFs for Chinese land since 2012. It would be useful to focus on the consequences of the GLOF in Chinese land around Aksu before the construction of the water reservoir and after the filling of the reservoir.

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