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Assessing changes of Ile Alatau glaciers and corresponding threats

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Author’s declaration

No portion of the work referred to in this thesis has been submitted in support of an application for another degree or qualification of this or any other university or other institute of learning.

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Abstract of Thesis submitted by:

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Climate change caused melting of glaciers in high mountain regions. Glacial mass loss in high mountain areas has direct impact on local settlements by creating water scarcity and hazardous disasters as a glacial lake outburst flood and mudflow. This research is focused on Ile Alatau mountain range and on Almaty city, which is largest city of Kazakhstan; financial and cultural center of the country, with population around 2 million people. The aim of research is to assess melting of Ile Alatau glaciers and corresponding threats to Almaty city. In order to address the research questions the combination of various methods was used: historical data collection, Remote Sensing, GIS. Changes of glacier surface area and development of glacial lakes in Ile Alatau mountain range between 1972 and 2016 was assessed by using Landsat images. The impact of glacial mass loss on local surface water resources and threat of GLOF in Almaty city was investigated. Disaster management plan of the city, past active and passive preventive activities were examined; strong and weak points were identified.

Keywords: GIS, Remote Sensing, Melting of glaciers, GLOF, Disaster Management, Almaty, Ile Alatau.

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Table of Contents

List of Figures

List of Tables

List of Appendices

List of Abbreviations

DEM – Digital Elevation Model

GIS – Geospatial Information System

GLOF – Glacial Lake Outburst Floods

NDSI – Normalized Difference Snow Index

NDWI – Normalized Difference Water Index

USGS – United States Geological Survey

1. Introduction

1.1 Problem definition and background

Climate change has a negative impact on the whole world and consequences of this phenomenon increase year after year (Samjwal Ratna Bajracharya 2009; Samjwal Ratna Bajracharya, Mool, and Shrestha 2008; Aizen and Aizen 1994). Melting of glaciers is one of the most important issues that climate change creates (Aizen et al. 1997a). Melting of glaciers in high mountain area could be source of threats as shrinking of surface water resources and glacial lake outburst floods (GLOFs) (Khromova, Dyurgerov, and Barry 2003). 27% of the glacier mass was melted in the last 50 years in Central Asia (IG 2010). In the same time Ile Alatau mountain range lost around 41% of glacier mass (IG 2010). Catastrophic Glacial Lake Outburst Floods were happened in 1963, 1973, 1977 in Almaty and nearby areas (Tobias Bolch et al. 2011). Last significant GLOF in Almaty was happened in July 2015. Around 1000 people were evacuated, 127 homes were damaged, 76 people were injured (“NASA” 2015). This accident happened accidentally and people were not ready for such an event.

Melting of glaciers is a big challenge for our future. In the worst scenario, glaciers of Ile Alatau mountain range could disappear in 2100 (IG 2010). In order to protect the city from glacial lake outburst floods during the melting of glaciers highly developed disaster management plan and monitoring by using new technologies are required.

1.2 Research Aim

The aim of research is to assess melting of Ile Alatau glaciers and corresponding threats to Almaty city.

1.3 Research Questions and Objectives

The research will focus on three research questions:

RQ-1. How much have glacier area of Ile Alatau mountain range been changed since 1970s?

- To assess changes of glacier surface area in Ile Alatau mountain range
- To analyze changes of precipitation and temperature

RQ-2. What are the threats from melting of glaciers to local settlements?

- To investigate threats from melting of glaciers to local settlements

RQ-3. What are the threats of Glacial Lake Outburst Floods to Almaty city?

- To analyze threats of glacial lakes to the city
- To assess existing disaster management plan of the city

1.4 Outline

Chapter 2 provides the brief literature review on global climate change and related consequences. This chapter also covers threats from melting of glaciers in Central Asia, especially GLOFs and depletion of surface water resources in the second part. In third part of this chapter were overviewed existing techniques of assessing melting of glaciers and related threats by using GIS and Remote Sensing. In fourth part of this chapter were analyzed disaster risk reduction plans in the world. Chapter 3 provides the short description of utilized methods. Chapter 4 presents analysis of glacier depletion in Ile Alatau mountain range. In first part of this chapter were described results of changing glacier surface area in Ile Alatau assessed by using Landsat images and ArcGIS. Second part of the chapter provides analysis of climate conditions in high mountain areas of Ile Alatau between 1935 and 2006. Chapter 5 covers corresponding threats of glacier depletion. The first part of chapter presents analysis of role of glacier on local water resources. The second part of the chapter presents assessment of developing glacial lakes from 1972 to 2016 and analysis of past GLOF events. Chapter 6 covers analysis of threats of GLOFs in Almaty. It covers overview and discussion of present disaster management plan of

Almaty city and examines emergency response of state in case of GLOF. The concluding chapter 7 presents summary of the results and author's analysis of findings within the context of the research aim.

2. Literature review

2.1 Impact of Global Climate Change on glaciers of Central Asia

Climate change has quickly developed after industrial revolution, and nowadays has vast negative impact on the nature and humankind. According to IPCC (2001) global average temperature has increased by approximately 0.75˚C in the last century and continuing to increase year after year. Each year from 1880 to present is recorded as hottest year, and according to the climate models global temperature between 2030 and 2060 will increase to 2-5 ˚C (IPCC 2007; Bajracharya 2009) . One of the main consequences of climate change is melting of glaciers (Bajracharya *at al.* 2006; Bajracharya and Mool 2009; Bajracharya, *et al.* 2008, IPCC 2001; Oerlemans 1994). Central Asia, as well as Alaska, is one of the main leaders on glaciers melting, and it shows the large depletion of glacier-ice (Arendt *et al.* 2002; Khromova *et al.* 2003). The Hymalaian glaciers are shrinking and the glacier surface area is lowering since the early 1970 (Bajrachaiya and Mool 2009; Khromova *et al.* 2003; Paul *et al.* 2004). The Tian Shan and Pamir-Alai glaciers had a serious mass loss in 1940-1947 and 1973-1985, and totally lost about 5% - 7% of their mass between 1935 and 1985 (Aizen and Aizen 1994; Aizen *et al.* 1997).

Since glaciers are the main source of surface water, their depletion has influential impact to the Caspian – Aral, Balkhash, Issik Kul, Tarim and other Central Asian water basins (Aizen *et al.* 1997). Because of the sharply continental climate glaciers collect the solid precipitation during the winter and provide lowlands with water during the summer period, which creates condition for development of agriculture (Hagg *et al.* 2007; UNEP 2007; Narama *et al.* 2010). Because of changes on temperature and precipitation process of glacier formation during the winter season cannot contribute enough mass of ice compared to the melting mass during the summer (Medeu 2011). That is how climate change leads to glacial mass loss and particularly affects water availability, energy and food security in many countries (Maas *et al.* 2012). Melting of glaciers could also be cause of disaster events as Glacial Lake Outburst Floods (GLOFs) (Blagovechshenskiy *et al.* 2015; Tobias Bolch *et al.* 2011). Glacial lakes that developed on the foot of glaciers can create debris and mud flow, which has hazardous effect to infrastructure and inhabitants (C. Huggel *et al.* 2003). In that case Tian Shan Mountains play an important role for Central Asian countries. Recent studies about glacier cover in Tien Shan Mountains (Aizen e*t al*. 2006; Liu *et al*. 2006; Narama *et al*. 2006; Narama *et al.* 2010; Shangguan *et al*. 2006; Bolch 2007; Li *et al*. 2007; Niederer *et al*. 2008; Sorg et al. 2012; IG 2010) have shown substantial glacial mass lost. Naramata *et al.* 2010 selected four study regions in the Tien Shan Mountains: (1) the Pskem, which includes Ugam, Maidantal, and Pskem ranges and western part of Talas range; (2) the Ile-Kungey region that includes Ile Alatau and Kungey Alatau ranges; (3) At-Bashy region; and (4) SE-Fergana region (Naramata *et al.* 2010). After assessing of glaciers melting in taken four regions it was identified by that large glaciers shrinkage between ~1970 and ~2000 was determined in the Pskem region (19%) and Ile-Kungey region (12%) (Narama *et al.*2010). In the time period between 2000 and 2007 these numbers were 5% in Pskem region and 4% in Ile-Kungey region (Narama *et al.* 2010). Other studies (Bolch 2007; Sorg *et al.* 2012) also show 16-32% of glaciers area lost in the Ile-Kungey region between 1955 and 1999. Since Ile Alatau and Kungey Alatau mountain ranges are located close to each other, and divided by relatively small plateau, and also both of them always fully fit into one Landsat image, they probably were studied together as an Ile-Kungey region. Because of that there is no recent studies done by using Remote Sensing that cover only Ile Alatau mountain range.

Ile Alatau is a mountain range located in northern Tian Shan in territory of Kazakhstan and Kyrgyzstan. This mountain range feeds several rivers and supply with water Balkhash Lake as a part of Ile River basin and has significant impact to agriculture in the lowland area of

Zhetysu region. On the foot of this mountain range locate several towns and the biggest city of Kazakhstan – Almaty. Almaty is a cultural and financial center of Kazakhstan. Population of this city is around 2 million. Since climate change has huge impact on glacier depletion in central Asia, Ile Alatau mountain range, as a part of Tian Shan Mountains, has high level of glacier mass lose. These changes on glacier mass balance could have several consequences as shrinking of water sources and appearing glacial lakes with danger of GLOFs. That is why glaciers related threats create vulnerability in this region, and complex study of glacier melting and related consequences are required.

2.2 Corresponding threats

2.2.1 Shrinking of surface water resources

Water is one of the main resources in Central Asia. Water is mostly needed for agriculture in Kazakhstan and Uzbekistan, and for energy production in Kyrgyzstan and Tajikistan (Nazarmuhamedov 2012). Climate of Central Asia is mostly hot and dry during the summer and very cold with high snowfall during the winter. In short term glaciers collect solid precipitation during the winter and create runoff of melted water during the summer. This process helps to keep stable water availability in the region. In long term depending on the dominantly dry or wet year glaciers store precipitation for couple of years or decades, and transport them through the time. Before the end of little ice age the mass of present glaciers was formed, and nowadays, in term of global warming, glaciers are losing historically formed ice cover (Aizen *et al.* 1997a; Arendt *et al*. 2002). According to the Krenke (1980) in 80^{th} of last century 1580 km^3 of fresh water was stored in the Central Asian glaciers. Between 60^{th} of last century and 2010 27% of glacier mass in Central Asia was depleted (IG, 2010), and increasing of temperature by 2100 (IPSS 2001) is likely to lead 43-81% glacier loses in Pamirs and Hymalayas (Shangguan *et al.* 2006a). 50% glacier loss is expected in Tien Shan according to models assuming the 2 x CO_2 scenario for 2050 and 2075 (Hagg *et al.* 2007). Since melted glaciers' water creates about 30% of river drainage for the year and together with melted snow form more than 70% of renewable water resources of Central Asia (IG 2010), glacier melting has significant influence on water availability, and it could create a water scarcity in 21th century.

2.2.2 Glacial Lake Outburst Floods

One of the main and hazardous consequences of glacier melting is Glacial Lake Outburst Floods. Since global warming has a significant influence on glacier mass, it leads to the formation of moraine-dammed glacial lakes (IPCC 2007; Carey *et al.* 2012). When glaciers melt they create flat or deepened sites where glacier's tongue had been, so unbalanced glacial lakes, that have high potential for GLOFs, are formed in these sites (Ames 1998; Carey *et al.* 2012). Other glacial hazards as avalanches and rock slopes can occur because of high temperature that affects glacier or permafrost (Huggel 2009). Avalanches can also create displacement waves in the glacial lakes and generate GLOFs (Kershaw *et al.* 2005; Huggel 2003).

Glacial lakes intensively started to develop after so-called Little Ice Age (1550-1850) that is why they can be found in high mountains where glaciers are present (Mool *et al.* 2001; Bradford and O'Sullivan 2013). Every glacial lake has own dam that stores water and creates lake. Breach of this dam creates GLOF. Factors that lead to dam breach could be: (1) washout of crossing points of the lake because of high level of humidity and high temperature that make moraine dam wet and weak; and (2) rapid accumulation of melted water and precipitation (Yafyazova 2007; Watanabe *et al.* 1994; Hambrey *et al.* 2008). Depending on volume of glacial lake, GLOFs can generate disastrous floods that destroy infrastructure and kill thousands of people (Ives *et al.* 2010; Bradford and O'Sullivan 2013). Even small lakes can cause serious damage, because outburst floods usually create debris and mud flow with volume much higher than lake by itself (Huggel *et al.* 2002; (Yafyazova 2007).

Most sources of GLOFs in Central Asia are located in Kyrgyzstan, Tajikistan, and Kazakhstan (UNDP 2011). 287 lakes in Kyrgizstan were identified as liable to failure in 1999. About 70 GLOFs happened between 1952 and 2007 in this country, and settlements, agricultural lands, roads and other infrastructures were damaged; several hundred people were died (UNDP 2011). Recent studies in the Southwestern Pamir has presented that 6 glacial lakes were defined as extremely hazardous and 16 lakes as hazardous; totally 428 glacial lakes were identified

(UNDP 2011). GLOF hazards in Kazakhstan are the greatest in Ile Alatau mountain range, that has 186 glacial lakes, and Zhetysu Alatau mountain range, that has 577 glacial lakes (Blagovechshenskiy *et al.* 2015).

2.3 GIS and Modeling on assessing melting of glaciers and related threats

Various techniques could be used for studying melting of glaciers and related threats. Glaciers locate in high mountain areas and coverage area of them could reach several hundred square km. For example, glaciers of Ile-Kungey region are located in elevation from around 3000 up to around 5,000 meters, and cover area about 560 km^2 (Narama *et al.* 2010). Because of that it is difficult, time consuming and more expensive to do field research and frequent monitoring. In that case geospatial technologies as satellite images and remote sensing could help to study big areas in various period of time. Other feature of these approaches is an open access to data from the past, which means that there is ability to analyze condition of exact area in last century. However, accuracy of data could have uncertainties because of resolution of satellite image. Resolution of recent satellite images from open sources can be 15-30 m. However, 5 m resolution images are also recently introduced, but they are not available for every country and not free of charge yet.

Geographic Information System (GIS) is a tool that helps to collect, analyze and put together different types of information as remotely sensed imagery, vector and raster data, and so on. Spatial references and data analysis as well as support on decision making are main strong points of this tool.

Remote Sensing is "… extraction of the data about an object from distance, without any physical contact, most often from satellites and aircrafts" (Kvasha 2014). As it seen in Figure 1, satellites detect reflected solar radiation from the object and by analyzing them provide different data about surface of object (Liew 2001).

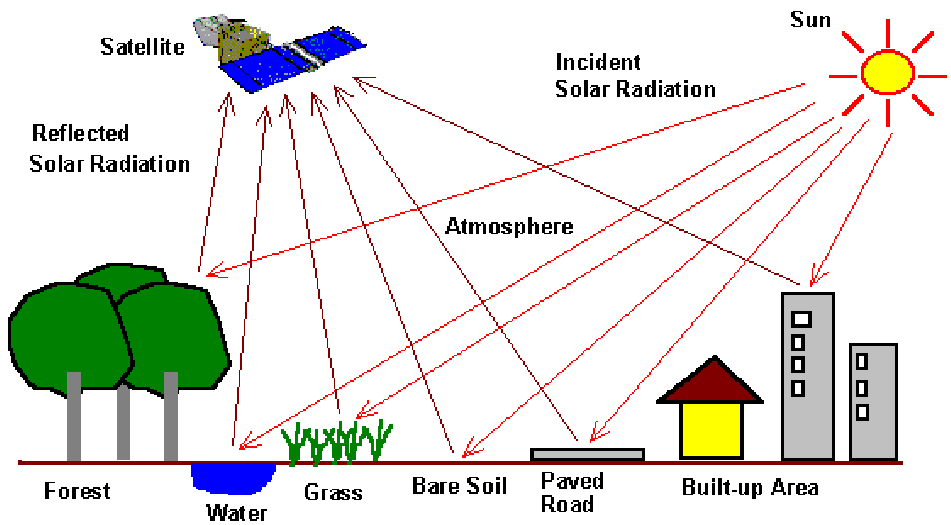

Figure 1Optical Remote Sensing. Source: (Liew, 2001)

Data processing of remotely sensed data is usually carried out by GIS tools. Several studies on assessing dynamic of glacier changes were done by using remotely sensed data and GIS tools (Aizen *et al.* 2006; Khromova *et al.* 2003; Narama *et al.* 2006; Narama *et al.* 2010; Niederer *et al.* 2008; Bolch 2007; Goerlich *et al.* 2017; Pieczonka *et al.* 2015; Farinotti *et al.* 2015). In these studies, mostly were used data from Landsat and ASTER/SRTM3-DEM. According to the Bolch (2007) average glacier depletion in the valleys of northern Tien Shan between 1955 and 1999 is more than 32% (Bolch 2007). According to the Khromova *et al.* (2003) retreat of glaciers in Ak-Shirak Range in the Central Tien Shan between 1973 and 2001 was 20% (Khromova *et al.* 2003).

Several studies were done by using Remote Sensing for identification of glacial lakes (Huggel *et al.* 2002; Bolch *et al.* 2008; Blagovechshenskiy *et al.* 2015). According to the Bolch *et al.* (2011) in 2007 were identified 132 lakes in northern Tien Shan (Bolch *et al.* 2011). According to the Blagovechshenskiy *et al.* (2015) 186 glacial lakes was identified and mapped in Ile Alatau mountain range in 2015.

There is also powerful method as modeling that can be used on assessing threats of glacial lake outburst floods. Models can be used for simulation of various events including floods and debris/mud flows.

One of the suitable approaches for modeling glacial lake outburst flood and for identification downstream area, that could be affected, was introduced by Huggel *et al.* (2003). So called modified single-flow model (MSF) was developed to model mass movement based on D8 flow direction algorithm (Huggel *et al.* 2003). In recent studies on identification and hazard assessment of potential dangerous glacial lakes in northern Tien Shan (Bolch *et al.* 2011) was used MSF as an approach to calculate possible area would be affected. Instead of MSF there are several one-dimensional (1D) Hydraulic Models as HEC-RAS and two-dimensional (2D) models as RAMMS and Flow-R on modeling floods, water-sediment flow, bam breach and debris flow. Modeling of GLOF can provide us with information about speed and volume of mudflow, about distance and potential affected area, and so on.

2.4 Disaster Risk Reduction plans

Glacial Lake Outburst Floods (GLOFs) is one of the most dangerous glacial hazards in high mountain areas that lead to risks related to social and economic losses (Huggel at al. 2004; Richardson and Reynolds 2000; Hoffmann and Weggenmann 2013). Because of global warming and melting of glaciers frequency of these flood events will increase (C. Huggel et al. 2003; Siegfried et al. 2012). In order to protect settlements in high mountain areas from risk of GLOFs effective Disaster Management Plan has to be created.

Responses of different city governments to climate risk are linked to disaster preparedness and risk reduction strategies (Solecki et al. 2011). In order to decrease risk from GLOFs, hazard assessment and preparedness planning; identification and monitoring potential dangerous glacial lakes; well-structured city development plan and structural and nonstructural hazard mitigation activities are needed (Carey *et al.* 2012). In case of GLOFs social vulnerability depends on the way of people dealing with these events and their reaction to material as well as human loses. Identified potential vulnerable areas and well-structured city development plan as well as early warning system can help to prevent human loses in case of flooding (Carey *et al.* 2012). Identification and frequent monitoring of potential dangerous glacial lakes can help to decrease risk of GLOFs and will contribute to act immediately in case of reaching high level of risk (Hegglin and Huggel 2008).

Since glacial lakes occur in high mountain areas in most cases they are difficult to reach. Identification and monitoring of these glacial lakes are difficult in terms of physical capability and defines as time consuming and economically inefficient. In that case research based on using satellite images and remote sensing can be very useful and effective. Several studies on hazard and risk assessment (Solecki *et al.*2011; Hegglin and Huggel 2008; Carey *et al.* 2012); on identification of potential dangerous glacial lakes (Huggel *et al.* 2002; Huggel *et al.* 2003; Bolch *et al.* 2011; Blagovechshenskiy *et al.* 2015) were done by using remote sensing and modeling.

3. Methodology

3.1 Research design

In order to assess threats of Glacial Lake Outburst Floods to Almaty city and examine city disaster management plan thesis was divided into two main stages (Table 1).

	Research question	Objectives	Steps	Methods
RQ-1	How much have glacier area of Ile Alatau mountain range been changed since 1970s?	To assess changes of glacier surface area in Ile Alatau mountain range	Identification of glaciers in satellite images	Data collection; Data analysis (GIS and Remote Sensing)
			Calculation of glacier areas and creation of map of changes	
		To analyze changes of precipitation and temperature	Analysis of data from different sources; creation of tables and graphs	Data collection
RQ-2	What are the threats from melting of glaciers to local settlements?	To investigate threats from melting of glaciers to local settlements	Analysis of influence of glaciers to local surface water sources	Data collection
			Assessment of changes of numbers of glacial lakes in taken area	Data collection; Data analysis (GIS and Remote Sensing)
			Investigation of past GLOF events in taken area	Data collection
RQ-3	What are the threats of Glacial Lake Outburst Floods to Almaty city?	To analyze threats of glacial lakes to the city	Investigation of past GLOF events in taken area	Data collection
			Mapping of potential dangerous glacial lakes	Data collection; Data analysis (GIS)
		To assess existing disaster management plan of the city	An overview of past and present activities on disaster risk reduction	Data collection
			Analysis of state's emergency response in case of GLOF	Data collection

Table 1 Research design

3.2 Data collection

Data collection is necessary at all two main stages of the thesis. Research was done through the review of books, scientific journals and other studies, both in English and Russian, at CEU library, National Library of Kazakhstan, National Academy of Sciences of Kazakhstan, and electronic resources. Legal documents as disaster management plan, city development plan, etc. were acquired from online database of responsible ministry of country. Statistical data, if to being more precisely data about glaciers melting in last century, meteorological data for last century, and other relevant historical data were collected from articles and reports prepared by other scientists as well as from relevant institutions during the research trip to Almaty. Necessary satellite images were gathered by using U.S. Geological Survey website, especially the EarthExplorer ("EarthExplorer" 2017) and the USGS Global Visualization Viewer ("GloVis" 2017). DEM that was required for the watershed delineation was downloaded from SRTM webpage ("SRTM Data Search" 2017).

3.3 Analysis

Satellite images processing and map creation was done by using ESRI ArcGIS 10 software package. Assessment of city disaster management plan was done by analysis of materials prepared during the data collection.

3.3.1 Assessing changes of glacier melting

Assessing of historical changes of glacier surface area was done by using satellite images Landsat from 1972 to 2016 (table).

Year	**Satellite**	**Bands**
1972 (07/Sep.)	Landsat MSS (Landsat 1-3)	Band 4 – Green Band 5 – Red Band 6 – Near Infrared (NIR) Band 7 – Near Infrared (NIR)
1978 (16/Aug.)		
1990 (07/Aug.)	Landsat TM (Landsat 4-5)	Band 1 – Blue Band 2 – Green Band 3 – Red Band 4 – Near Infrared (NIR) Band 5 – Shortwave Infrared (SWIR) 1 Band 6 – Thermal Band 7 – Shortwave Infrared (SWIR) 2
1999 (09/Sep.)		
2007 (19/Jun.)		
2016 (15/Sep.)	Landsat OLI/TIRS (Landsat 8)	Band 1 – Ultra Blue Band 2 – Blue Band 3 – Green Band 4 – Red Band 5 – Near Infrared (NIR) Band 6 – Shortwave Infrared (SWIR) 1 Band 7 – Shortwave Infrared (SWIR) 2 Band 8 – Panchromatic Band 9 – Cirrus Band 10 – Thermal Infrared (TIRS) 1 Band 11 – Thermal Infrared (TIRS) 2

Table 2 Different types of Landsat satellites for different years of interest and their band characteristics

In order to differentiate glacier cover from shade, lakes, and other objects Normalized Difference Snow Index (NDSI) was applied by employing SWIR and Green bands

(Green – SWIR/Green + SWIR). By using Unsupervised Classification identified glacier cover was delineated. From classified layer was created polygon, and surface area was calculated.

3.3.2 Assessing dynamic of changes of glacial lakes

Development of glacial lakes was assessed by using Landsat images from different years from 1972 to 2016 (table). Identification of glacial lakes was done by using Normalized Difference Water Index by employing NIR and Green bands (Green – NIR/Green + NIR). Unsupervised Classification was used for delineation of identified glacial lakes. Misclassified cells were corrected manually according to the Composite band. Number of lakes and surface area were calculated. The volume of the lakes was calculated according to the formula suggested by Huggel et al. (2002): $V = 0.104A^{1.42}$

4. Melting of glaciers in Ile Alatau mountain range

Ile Alatau mountain range is part of northern Tien Shan Mountains between Kazakstan and Kyrgyzstan. It is located in southern east of Republic of Kazakhstan and plays important role on supplying local settlements with water as well as on regulation of climate not only in local level but in whole Central Asia (IG 2010). The highest peak of Ile Alatau is Talgar peak (4978 m). Literature review was shown that Global Climate Change affected Central Asia and caused glacier mass loses. Since Ile Alatau mountain range plays important role for Southern East Kazakhstan assessing changes of glacier area and corresponding threats is important to understand the impact of glaciers for local settlements. Since the most studies that were done in Central Asia are investigated Ile Alatau and Kungey Alatau mountain ranges as a one Ile-Kungey region, separated assessment for Ile Alatau was needed.

4.1 Assessing changes of glacier surface area from 1972 to 2016

Assessing changes of glacier surface area was done by using Landsat images from 1972, 1978, 1990, 1999, 2007, and 2016. These images were obtained from open sources, so images with less cloud cover and good quality for taken area of interest were found only for these years. June, July, August and September were chosen as suitable months for research because of relatively high temperature and smaller amount of precipitation in the year, which means less seasonal snow cover in high mountains. Identification of glacier was done by using Normalized Difference Snow Index (NDSI) and Normalized Difference Glacier Index (NDGI). In most cases was used NDSI rather than NDGI because of uncertainty of Normalized Different Glacier Index during the classification. Taken layer from NDSI were used for unsupervised classification. Number of classes by default have to be ten times more that number of bands, but as more number of classes are used so more precise results could be taken. Depending on quality of image, in this research better results were reached with 30 and 50 classes. However, since NDSI was used, glaciers were recognized within two or four classes regardless of total number of classes. Classes with glacier area were selected and extracted by already created study area mask. Taken layer was converted from raster to polygon, and surface area was calculated (Figure 2). Misclassified cells were delineated manually according to the RGB composite band with. Accuracy assessment for images from 1990 was based on high resolution images from Google Earth and ArcGIS Online.

Maps of glacier surface area of Ile Alatau mountain range for each year of research are presented in Appendix 1.

Appendix 2 presents outline of polygons and show changes of glacier surface area in different years.

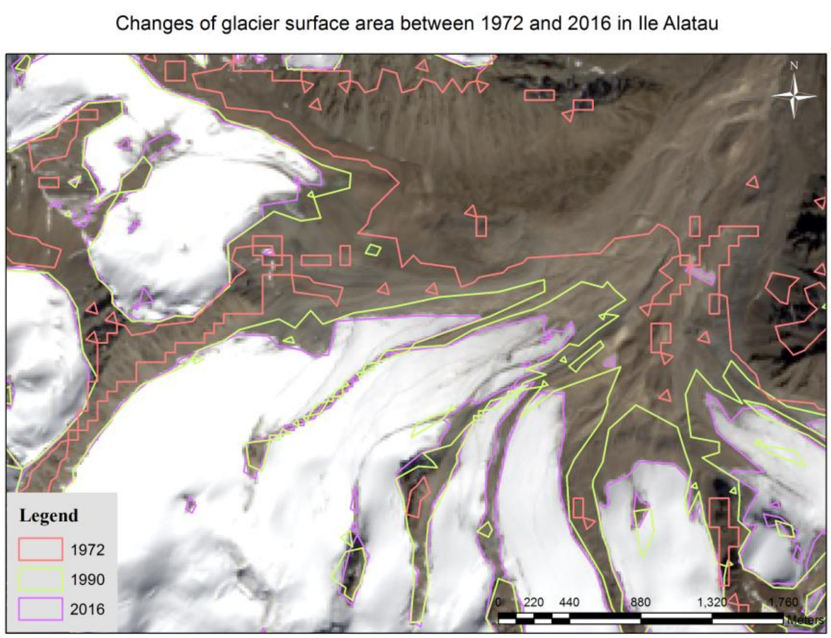

Figure 2 Changes of glacier surface area between 1972 and 2016

Changes of glacier surface area can be seen in Table 3.

<table>
<tr><td></td><td>1972</td><td>1978</td><td>1990</td><td>1999</td><td>2007</td><td>2016</td></tr>
<tr><td>Surface area, m^2</td><td>510,926,400</td><td>367,603,200</td><td>401,444,100</td><td>350,608,500</td><td>299,196,900</td><td>344,256,300</td></tr>
<tr><td rowspan="4">Changes,

%/year</td><td colspan="2">(-) 22.9</td><td colspan="2">(-) 12.66</td><td colspan="2">(+) 15.06</td></tr>
<tr><td></td><td colspan="2">(+) 9.2</td><td colspan="2">(-) 14.66</td><td></td></tr>
<tr><td colspan="3">(-) 21.43</td><td colspan="3">(-) 1.81</td></tr>
<tr><td colspan="6">(-) 32.62</td></tr>
</table>

Table 3 Total surface area of Ile Alatau glaciers and percentage of changes in different period of time. (-) - decresing; (+) - increasing

As we can see from results glacier surface area intensively decreased in 1970s with average speed of 3.8 %/year, and in 2000s with average speed of 1.83%. 1990 shows results higher than other years except 1972. The reason of that could be the existing of seasonal snow cover in the image or positive ablation of glaciers during that year. Since satellite images for 1980s were not used because of high cloud cover and low quality of image, the process of depletion of glaciers between 1970s and 1990s is unknown. However, outline polygons of glaciers Appendix 2 decreasing of surface area in 1990 as well. Increasing of glacier surface area between 2007 and 2016 also can be explained by positive ablation, as well as climatic and meteorological conditions of the year.

Overall glacier surface area between 1970 and 2016 decreased to 32.62%. Average speed of depletion was 0.75 %/year. Since changes of glacier surface area directly depends on climatic conditions, changes of temperature and precipitation between 1970 and 2016 have to be assessed.

4.2 Climate change

Climate change in Ile Alatau mountain range was assessed by using data from meteorological station Mynzhylky located in high mountain area 3017 m above the sea level.

Mynzhylky started to operate in 1935. Data about precipitation and temperature collected in this meteorological station between 1935 and 2006 was published by Vilesov (2007) (Figure 3).

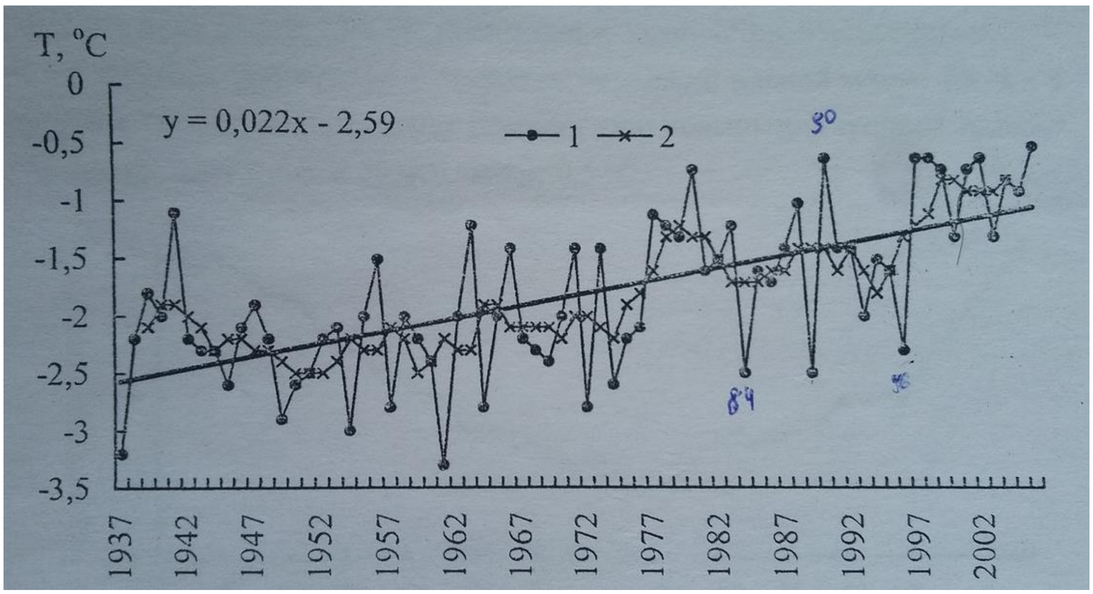

Figure 3 Changes of avarage year temperature (1) and changes of avarage temperature for five years (2) between 1937 and 2006 in Mynzhylky (Y- temperature, ˚C; X – years) (Vilesov 2007)

It can be seen that temperature average year temperature slightly increased in taken period of time. From 1972 to 2006 temperature increased to about ~0.7˚C. According to that data minimum average year temperature between 1972 and 2006 was minus 2.8˚C (1972), and maximum average year temperature was minus 0.5˚C (2006); the coldest month in that period of time was December of 1984 (minus 18.1˚C), and the hottest month was August of 1984 (plus 9.0˚C). Average year temperature increased with speed of 0.3˚C/10 years. Average winter temperature for decade increased to 1.4˚C from minus 10.9˚C to minus 9.5˚C since 1970s;

average summer temperature for one decade increased to 1.1˚C from 6.5˚C to 7.6˚C since 1960s, which means that average year temperature increased mostly because of winter seasons (Vilesov 2007).

Minimum average amount of year precipitation between 1972 and 2006 was 650 mm in 1997; maximum average amount of year precipitation was 1197 mm in 1966 (Figure 4) (Vilesov 2007). Rate of average year precipitation for 1935-2006 was 851 mm. The last two decades of 20th century show average amount of year precipitation of 876 mm, which is 103% of rate. For the first 6 years of 21st century this number was 898 mm, which is 106% of rate. It means that from the middle of last century amount of precipitation was increased with speed of 1.6 mm/year.

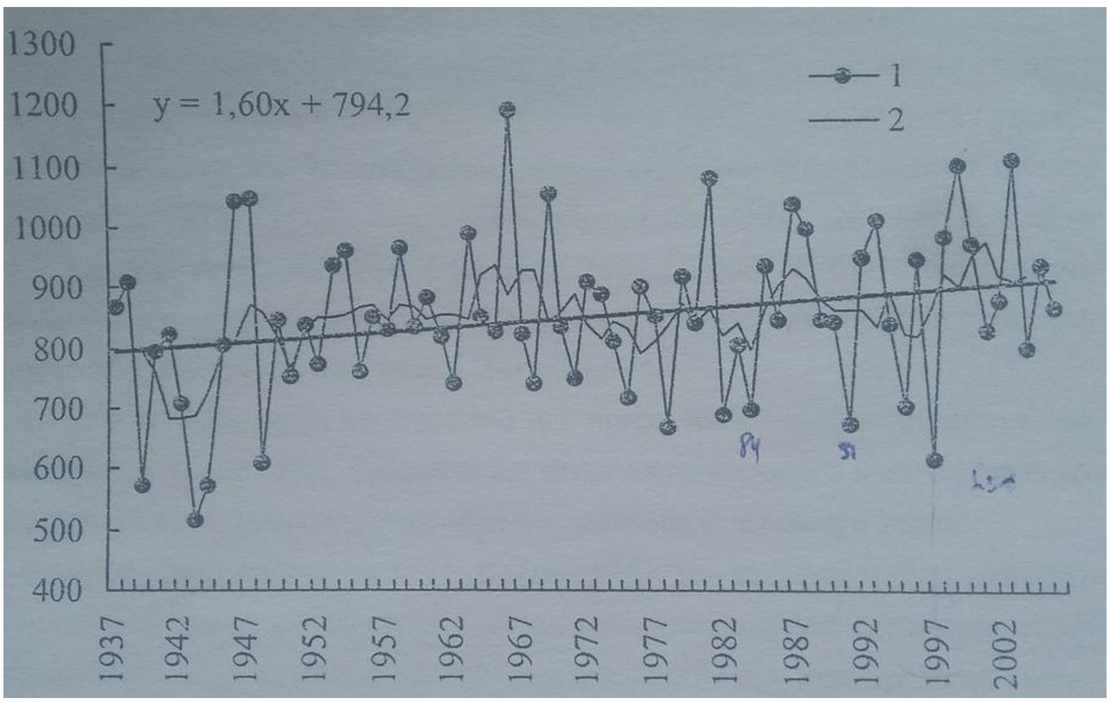

Figure 4 Changes of average amount of year precipitation (1) and avarage amount of five year precipitation (2) between 1937 and 2006 in Mynzhylky (Y – amount of precipitation, mm; X - years) (Vilesov 2007)

Increasing of temperature affected hydrological process, and caused the melting of glacier and the increasing of water volume in rivers. It also increased evaporation, and because of that amount of precipitation was increased as well. Increasing of winter temperature does not affect process of glacier formation until reaching the melting point, but changes of temperature in spring and autumn lead to increasing of length of hot season, and it cause negative ablation and loss of historical ice mass. Amount of solid precipitation can positively contribute to glacier formation, but because of climatic conditions of region 72% of precipitation falls from April to August, mostly during the hot season; and 28% falls from September to March, mostly during the cold seasons. Since temperature increasing, amount of precipitation increase mostly in hot season, which means less contribution on glacier formation. Moreover thermodynamic and physical processes between ice and water catalyze depletion of glaciers. However, increasing of precipitation has positive impact on development of agriculture.

5. Corresponding threats

5.1 Glaciers as a source of fresh water

Glaciers as a source of water play important role on feeding the rivers during the hot seasons. Melting of glaciers could develop water scarcity in high mountain regions. However, climatic factors of Central Asia create independent hydrological circulation, which means that water level of rivers mostly depends on wet precipitation and snow runoff. In order to examine impact of melting of glaciers on the water volume of rivers, data about percentage of glacial drain in the rivers' volume was obtained from Institute of Geography of Kazakhstan (Table 4).

	1975-1990	**1991-2008**	**1975-2008**
Uzynkargaly	8.4	0	3.5
Kaskelen	6.4	1.3	3.8
Kargaly (Kargalinka)	8.2	0	1.7
Ulken Almaty (above the Ulken Almaty Lake)	16.8	3.3	21.9
Ulken Almaty (total)	10.6	0.7	5.1
Kishi Almaty	4.2	4.5	2.7
Talgar	20.9	9.4	14.6
Issyk	10.2	8.4	9.2
Turgen	7.7	0.9	3.9
Total	12.1	3	6.6

Table 4 Portion of glacial drain in the rivers of Ile Alatau, %

As we can see during the intensive melting of glacier between 1972 and 1990 percentage of glacial drain in river volume was higher than period between 1990 and 2007. In both periods depletion of glacial mass was relatively intensive. The reason of that can be increasing of precipitation in last decades of 20th century. However, between 1972 and 1990 surface area of Ile Alatau glacier decreased to 32.62%, but percentage of glacial drain in rivers was lover than 20%. It means that melting of glaciers does not affect water volume of local rivers because of increasing of amount of precipitation.

Ulken Almaty and Kishi Almaty rivers are essential part of Almaty city. Besides creating parks and zones for vocation these rivers supply with fresh water the city and nearby irrigated areas. The first water supply and waste water treatment system of Almaty city was developed in 1931. Since 2008 water supply system of the city is served by state utility company "Almaty Su holding" that has three bodies: "Tospa Su" – responsible for waste water; "Su Zhelisi" – responsible for pipelines, access of residents to water; "Bastau" – responsible for fresh water supply. According to the "Bastau" about 1 million m^3 water is produced by water intake constructions every day ("Bastau" 2017). Around 24,000 m^3 water comes from surface water resources, especially from Kishi Almaty River and Kim-Asar River. The rest of it comes from ground water ("Bastau" 2017). Since glaciers help to keep balance between cold and hot seasons, the role of glaciers on water availability in irrigated land is important. However, despite glacier mass loses in the last century, volume of water in rivers were stable. The reason of it could be that volume of water in that rivers are mostly dependent on precipitation and on melted snow, and/or glacial mass loses have not reached the significant point to affect runoff. But it should be noted that in this case was mentioned connection between runoff and surface ice, but there is also permafrost and ice, located underground, that is huge source of water. Melting of underground ice and permafrost could not be visible in satellite images by using methodology that we used, but contribution of them on water level of rivers could be very significant. Anyway, ground water supply service is well developed, so problems with fresh water availability for drinking purpose do not exist in that region yet. But further depletion of glaciers could create a lack of water in dry season, which will force residents to use ground water for irrigation, and this, obviously, will lead to the ground water depletion and fresh water scarcity.

In case of agriculture, rivers of Northern slope of Ile Alatau plays important role. Big Almaty Channel that was built in 1970s has huge impact to development of agriculture in taken area. This channel starts from Bartogai water reservoir in Shelek River and goes to Kurty water reservoir through Enbekshikazakh, Talgar, and Raiymbek districts as well as Almaty city by supplying them with fresh water for irrigation and various technical/private needs. Catchment area of Shelek River covers part of Southern slope of Ile Alatau and part of Northern slope of Kungey Alatau. The main source of water for rivers in this area is precipitation, but role of glacier is also important, especially during the dry seasons. Since amount of precipitation is low between July and September, development of agriculture in this area is directly depended on glaciers. So even if runoff was not significantly changed in last decades, future changes of climate and depletion of glacial mass could develop water scarcity in this region. Further studies about impact of glaciers and permafrost to hydrological cycle of the region by using different future scenarios are needed.

5.2 Glacial Lake Outburst Floods

5.2.1 Dynamic of changes of glacial lakes

One of the main consequences of melting of glaciers is creation of glacial lakes. In order to investigate connection between melting of glaciers and formation of glacial lakes in Ile Alatau mountain range dynamic of changes of glacial lakes were assessed. For that reason numbers of glacial lakes in 1972, 1978, 1990, 1999, 2007, and 2016 were calculated by using Landsat images and ArcGIS tool.

Identification of glacial lakes was done by using Normalized Difference Water Index (NDWI). By using unsupervised classification identified glacial lakes were delineated, and numbers of glacial lakes as well as surface area of each lake were calculated. The volume of the lake was calculated by using the formula suggested by Huggel *et al.* (2002): $V = 0.104A^{1.42}$, where 'A' is a surface area of the lake. It is important to take into account that according to the Bolch *et al.* (2011) an overestimation of the volume of the lake, calculated by this formula, could reach 20%, so this calculation may only serve as a first estimation.

Maps of glacial lakes of Ile Alatau mountain range are presented in Appendix 3.

Number of glacial lakes and their total surface area are presented in Table 5.

	1972	1978	1990	1999	2007	2016
Number of glacial lakes, n	56	36	97	100	287	187
Total surface area, m^2	799,200	601,200	735,300	1,226,700	1,760,400	1,388,700

Table 5 Number of glacial lakes in different years in Ile Alatau and their total surface area

As it can be seen, numbers of glacial lakes increased according to the melting of glaciers. Figure 5 show us some of the glaciers in Ile Alatau mountain range and glacial lakes located on the top of the glacial tongue in 1972. Figure 6 presents exactly the same area in 1999. According to these maps development of glacial lakes can be seen. Decreasing of surface area of glaciers creates hollows dammed by moraine of ice, water collected on these ponds named as glacial lakes. That is why depletion of glaciers is always accompanied with creation of glacial lakes. Sometimes glacial lakes can be harmoniously depleted by themselves by tunnels or channels, but in other cases they could reach thousands of square meters. In case of 1990 and 1999 it can be seen that number of glacial lakes increased to 3 more lakes, but total the surface area of the lakes increased to around ~65%. Figure 7 presents the same area as previous two maps, but in 2016. It can be seen that one lake was depleted, and two small lakes were joined into one big lake, surface volume of the lakes was increased.

Figure 5 Glaciers and developing of glacial lakes in 1972

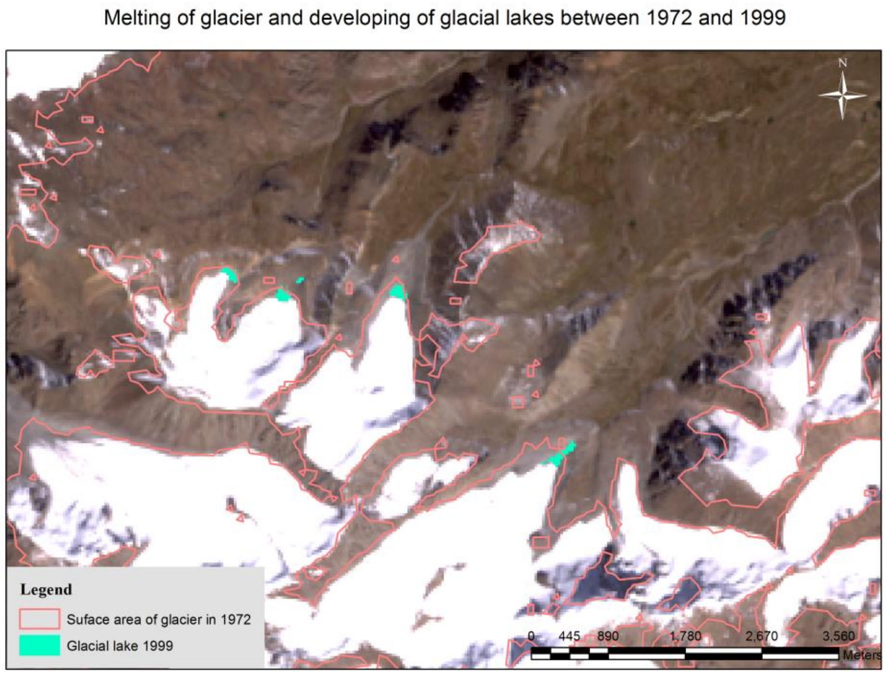

Figure 6 Melting of glaciers and developing of glacial lakes between 1972 and 1999

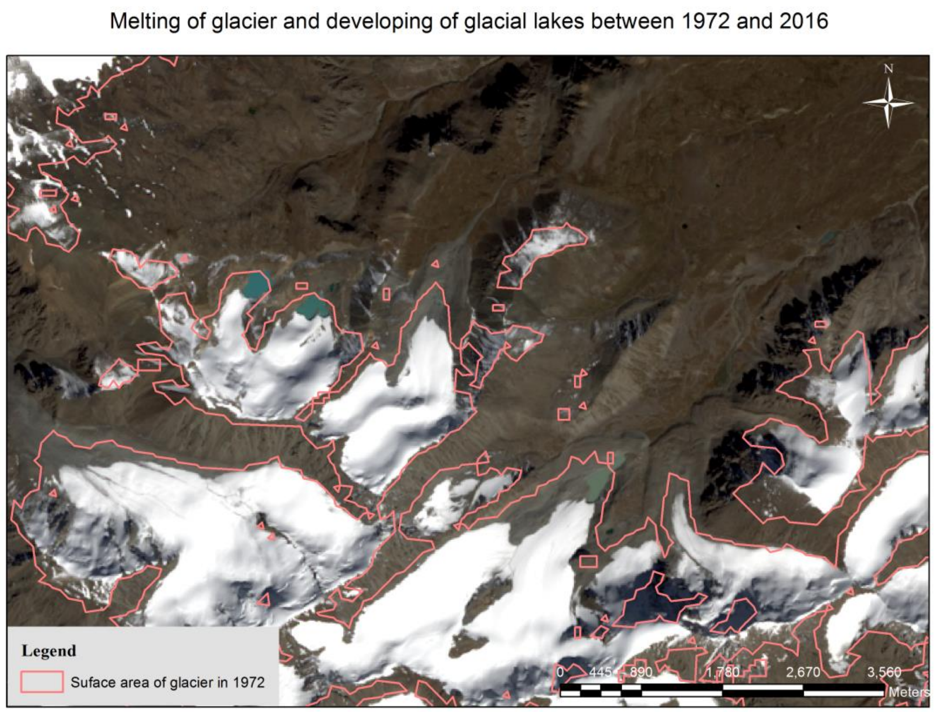

Figure 7 Melting of glaciers and developing of glacial lakes between 1972 and 2016

Breach of moraine/ice dam could develop the flood with high speed of discharge. It triggers hazardous mudflows, with volume much higher than lake's volume. A large number of lakes, developed in Ile Alatau mountain range, have threat of hazardous GLOFs for local settlements. A rapid increasing of glacial lakes in last decades creates dangerous situation in taken area, so in order to protect settlements from potential GLOF events, nature of the outburst floods has to be examined.

5.2.2 GLOF events

Glacial lakes are mostly unstable. Breach of moraine dam could develop Glacial Lake Outburst Flood which creates mud/debris flow (Yafyazova 2007; Medeu 2011). Danger of GLOF is higher in hot seasons when because of melting of permafrost and high intensity of glacier melting (Medeu 2011). So, as the most dangerous glacial hazard, GLOF events have to be assessed. In order to investigate the nature of GLOFs and the main triggers of them, past GLOF events in taken area were overviewed.

Table 6 presents significant GLOF events happened in previous hundred years.

Date	**Place**	**Volume of mudflow, m^3**	**References**
20/August/1951	Kishi Almaty river basin	200,000	(Birzhanov *et al.* 1998; Cherkasov 1953)
07/August/1956	Kishi Almaty river basin	1.1 million	(Birzhanov *et al.* 1998; Kaveckyi and Smirnov 1957; Kolotilin 1959)
06/July/1958	Zharsai-Esik river system	~ 4 million	(Birzhanov *et al.* 1998; Popov 1981)
07/July/1963	Esik river basin	5.8 million	(Zems 1976; Birzhanov *et al.* 1998)
15/July/1973	Kishi Almaty river basin	3.8 million	(Vinogradov *et al.* 1976; Plehanov *et al.* 1975)
3-4/August/1977	Ulken Almaty river basin	2.5-6.0 million	(Birzhanov et al. 1998; Osipova and Kazannikov 1982; Esenov and Degovec 1979)
29/June/1979	Middle Talgar river basin	120,000	(Birzhanov et al. 1998)
23/July/1980	Kaskelen river basin		(Kazglavselezashita 1980; Birzhanov et al. 1998)
23/July/2015	Kargaly river basin	`~ 70,000	(“NASA” 2015; “FloodList” 2015)

Table 6 GLOF events happened between 1950 and 2015

In 20th of August 1951 around 4 p.m. (local time) mudflow appeared in riverhead of Kishi Almaty river. Cause of this mudflow was GLOF that was created by underground dam breach in the glacial lake №2 located in 3350 m above sea level (Birzhanov *et al.* 1998). The value of mudflow was about 200,000 m^3 (Cherkasov 1953). This GLOF did not reach Almaty city, but destroyed natural landscape and bridges in the valley.

In 7th of August 1956 around 3 p.m. (local time) powerful water outburst was detected in the same glacial lake №2. Water discharge was about 25-40 m^3/c and it developed mudflow with discharge around 500-1000 m^3/c (Kaveckyi and Smirnov 1957). This GLOF destroyed infrastructure and caused serious material loses. Total volume of the mudflow was calculated as 1.1 million m^3. Because of the dam located lower of the valley, direction of mudflow was changed to the Esentai river that had profound and concrete walls (Kolotilin 1959).

In 6th of July 1958 GLOF event occurred in Zharsai-Esik river system. Mudflow was catched by Esik lake. This mudflow was triggered by breaching of lake located in 3400 m above the sea level by Zharsai glacier (Birzhanov *et al.* 1998). Observers of the lake after accident identified that cause of breach was underground tunnel which developed to the open channel later. Forested area between former lake and Esik lake was destroyed, open areas were covered with debris. First calculation of volume of the mudflow showed about 150,000 m^3, but further studies calculated it as more than 4 million m^3 (Popov 1981).

In 7th July 1963 in Esik river basin happened one of the biggest mudflows in Northern Tien Shan triggered by GLOF. Around 2 p.m. Esik lake located 1745 m above the sea level faced hazardous mudflow with volume of 5.8 million m^3. Trigger of this mudflow was breach of lake №17 (Zems 1976). Since Esik lake was famous touristic palace this mudflow destroyed a recreational area with high amount of tourists from Almaty and other regions. Speed of mudflow was 5-7 m/c. It created waves in Esik lake with height of 5.5 m and speed of 7.4 m/c. this process caused dam breach of lake with capacity volume of 17 million m^3. Outburst of Esik lake created bigger mudflow. Esik town and other settlements in down valley were destroyed, dozens of people were died (Birzhanov *et al.* 1998).

In 15th of July 1973 Kishi Almaty again was a place where hazardous GLOF happened. Around 6 p.m. (local time) huge amount of mud flowed down through the valley (Vinogradov *et al.* 1976). Volume of mud flow, which was cached by Medeo dam, was 3.8 million m^3 (more than three times bigger than mudflow occurred in 1956) (Plehanov *et al.* 1975). This hazard killed dozens of people and destroyed infrastructure as well as resort located on the valley. Building of Medeu dam was still in progress, and a construction for water discharge was not built yet. The whole water-mud mass was collected inside the dam, and moistening of dam basis could cause breach of the dam, that could trigger bigger mudflow. Only quick actions of several instructions helped to avoid creation of new outburst flood. Around 5 thousand people and hundreds machines were worked on emergency operations more than one month. Cause of this GLOF was breach of glacial lake № 2. Volume of this lake in that time reached 260,000 m^3, against 20,000 m^3 in 1951 and 32,000 m^3 in 1956 (Birzhanov *et al*. 1998). Only Medeu dam with 110 m height and quick reaction of appropriated institutions saved Almaty city from hazardous disaster.

One of the biggest and significant GLOF in Ulken Almaty river basin happened in 3-4th of August 1977. Cause of this GLOF was glacial lake №13 located nearby Sovetov glacier in 3400 m above the sea level. In August 1967 volume of the lake was 138,000 m^3; in July 1974 volume of the lake increased and was 220,000 m^3. In that situation was done activities on artificial decreasing level of water in the glacial lake №13, and in 1974-1975 volume of the lake decreased until 80,000-90,000 m^3 (Birzhanov *et al.* 1998). In 1976 and 1977 preventive works were stopped and in 1977 breach of moraine dam in lake №13 caused mudflow with volume around 2.5 million (Osipova and Kazannikov 1982) – 6.0 million m^3 (Esenov and Degovec 1979). This event had tremendous negative effect to infrastructure, and water supply facilities of the city were damaged. People were evacuated from dangerous areas, but since there were a lot of tourists and city residents that had a rest in the gorge, a lot of people died.

In 21st of June 1979 in Middle Talgar river basin occurred mudflow triggered by breach of lake №7 located in 3400 m above the sea level near Sportivnyi glacier. Mudflow with volume of 120,000 m^3 destroyed camp for alpinists named as 'Talgar' and contained 24 buildings that were fully destroyed. Fortunately, alpinist, tourists, and servicing personnel were informed in time through loudspeaker, and overall around one hundred people were evacuated from the camp (Birzhanov *et al.* 1998).

In 23rd of July 1980 in Kaskelen river basin another GLOF was happened. Glacial lake №16 located nearby glacier №25 was empty several years. Underground channels on hollow of the lake supported water flow coming from glacier. Because of closing this tunnels lake rapidly developed, and was full filled with water. At 8 a.m. volume of the lake reached 240,000 m^3 (Kazglavselezashita 1980). Outburst of the lake happened at 9 a.m. Several bridges, roads and private buildings were affected. Anti-mudflow institution already knew about threat of lake №16, that is why point of observation and notification was created there before the GLOF, so government as well as people were informed in time (Birzhanov *et al.* 1998).

In 23rd of July 2015 unnamed glacial lake located nearby Kargakinka glacier caused GLOF in Kargalinka river. Anti-mudflow dam cached significant amount of mudflow, but despite it the dam could not protect the settlements. 6 people were hospitalized, 78 were given medical assistance, 1,036 people were evacuated, and 127 houses were damaged. Bridges, roads, electricity and power lines as well as other private and state buildings were damaged (“FloodList” 2015; “NASA” 2015; “AkZhaik” 2015).

Trigger of moraine dam breach could be climatic factors, meteorological factors, and glacial factors. As we can see from events described above, the most of outbursts happened because of underground tunnels or because of melting of permafrost. Some of them happened because of ineffective on-site preventive activities, but these activities was done in order to avoid outburst of the lake by surface channels. GLOFs usually happen in very hot days, because of rapid increasing of melted water. Thermodynamic processes between water and moraine dam plays significant role on melting of moraines and permafrost, which develop dam breach.

Most of the GLOF events happened in 1950-1960 and in 1970-1980. Cause of these events can be explained by intensive melting of glaciers in that period of time.

Medeu and Almarasan gorges are located in Kishi Almaty and Ulken Almaty river basins. The Medeu, an outdoor speed skating and bandy rink located in Medeu valley 1,691 m above sea level, Shymbulak sky resort, located in upper part of Medeu valley at elevation of 2,200 m, the Big Almaty Lake, a natural alpine reservoir located in Almarasan valley at elevation of 2,511 m, are the most touristic places not only for the city residents but for the whole country. There is resorts, cams, hotels and other recreational areas for tourists that come here not only during the winter but also in hot seasons, when danger of GLOFs is high. Most of the dams locate in down part of valley, and that is why safety of these people is not guaranteed.

6. Threats of GLOFs in Almaty city

Almaty city locates in Northern slope of Ile Alatau mountain range. Melting of glaciers in Ile Alatau mountain range has direct impact to the city. Since three main rivers that flow through the city come from mountains, water availability and glacial hazards related issues affect Almaty city in several ways. Since impact of glacier melting to water availability was discussed in previous chapter, this chapter will be focused on threats of GLOFs in Almaty and on Disaster Management Plan of the city. Overview of GLOF events occurred in previous years proved that Almaty city has big issue related to the glacial hazards. Mudflows with volume of several million cubic meters were triggered by GLOFs, and even bigger hazards could affect in terms of Climate Change. Since Almaty is the one of the most populated and economically important city, it was decided to focus on this city.

6.1 Disaster management plan

To protect settlements and residents is the biggest issue related to the glacial hazards. Several activities on risk prevention were done in the past and several approaches were developed since the middle of last century when a lot of disasters were happened. These activities on prevention risk of GLOF could be divided into two groups: active and passive (Birzhanov *et al.* 1998; Medeu 2011). Passive activities are building of protective constructions as dams, channels, settlers, and so on. Active actions are reducing water level of lakes by building channels and tunnels, or strengthening of moraine dam's crossing points, or building other auxiliary engineering structures in glacial lake. Since on-site preventive activities have to be done in lakes with high level of danger, identification of potential dangerous glacial lakes is the most important unit of disaster management plan.

6.1.1 Potential dangerous glacial lakes

In order to protect the city, residents and tourists, identification and monitoring of potential glacial lakes are needed. Ministry of Internal Affairs has a Committee of Emergency Situations. “Kazselzashita” is an organization of Committee of Emergency Situations, which operates to protect people and settlements from debris and mud flow. This organization also deal with floods, mudflows, avalanches, and landslides. Since GLOF is one of the main triggers of hazardous mudflows in taken area, glacial lakes are one of the main focusing points of this organization. There are several observation points in the mountains serving by Kazselzashita. On site monitoring activities as well as observations via helicopter are also conducted by this organization (“Kazselezashita” 2017).

Kazselzashita has own regulations on identification potential dangerous lakes. According to that following criteria has to be exist: rapid increasing of water level; pouring out of water over the dam; appearance of water flow in cracks of glacial dams; appearance of underground tunnels; and appearance of rapidly developing new lakes. This approach based on aero-visual observation and ground observation. Aero-visual observation by helicopter is conducted frequently during the vulnerable period. Aero-visual observation allows to cover big area in short period of time. During the observation photos of glacial lakes have to be taken, and extra attention have to be given to the unstable, frequently breaching lakes as well as to the lakes with moraine and gracilized dam. Taken photos have to be processed, and according to the results ground observation have to be conducted. Ground observation is conducted every year and mainly focused on potential dangerous glacial lakes. During the ground observation glacier-moraine system, glacial lakes, cross points of lake’s dams have to be assessed. After aero and ground visual survey glacial lakes with high level of danger have to be identified, and next survey including use of different instruments has to be conducted. Results taken by this survey are used to create the full structure of glacial lake with surrounding conditions, and according to that on-site activities for decreasing level of water should be done if needed. Using of satellite images and remote sensing can help to identify potential dangerous lakes as well as new lakes in order to create a map of survey ("Kazselezashita" 2017). Of course, aero observation is better and precise than remote sensing, besides Almaty is very important city and enough effort is given to this area. But development of real time remote sensing monitoring could be very useful and economically effective. Using of drones would be also effective.

Recent studies on identification of potential dangerous glacial lakes (Bolch *et al.* 2011; Blagovechshenskiy *et al.* 2015) were done by using satellite images and remote sensing. According to the Bolch *et al.* (2011) 132 glacial lakes was identified in Ile Alatau mountain range in 2007. 47 of them were defined under medium and high danger category (Bolch *et al.* 2011). According to Blagovechshenskiy *et al*. (2015) by using data from 2002 and 2000 186 glacial lakes were identified in Ile Alatau mountain range, and 6 of them were defined as a lakes with very high level of danger.

However, Kazselzashita has own list of potential dangerous glacial lakes based on long term aero-ground observations and on experience. That is why it was decided to not include hazard assessment and identification potential dangerous glacial into scope of this research. Despite to that, map of glacial lakes was created in order to calculate the number of lakes and their surface area, as well as their volume. It was needed for analysis of protective dams of the city. This topic will be discussed below.

Identification of glacial lakes was done by using Landsat image from 2016. By using SRTM DEM with resolution of 90 m, and 'hydrology' tools in ArcGIS was created watershed of the city. According to that watershed were defined glacial lakes that locate in catchment area of rivers that belong to Almaty (Figure 8). By using recent satellite images were identified 24 glacial lakes that could directly affect Almaty city (Figure 9).

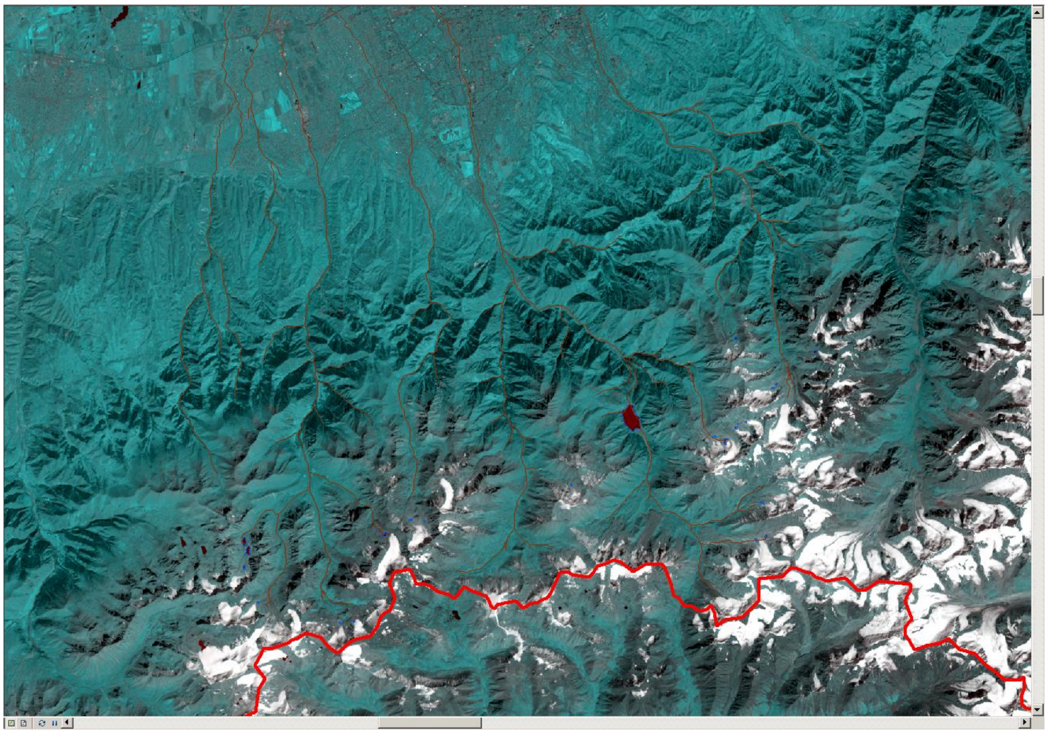

Figure 8 NDWI and creation of catchment area of rivers that belong to Almaty (screenshot)

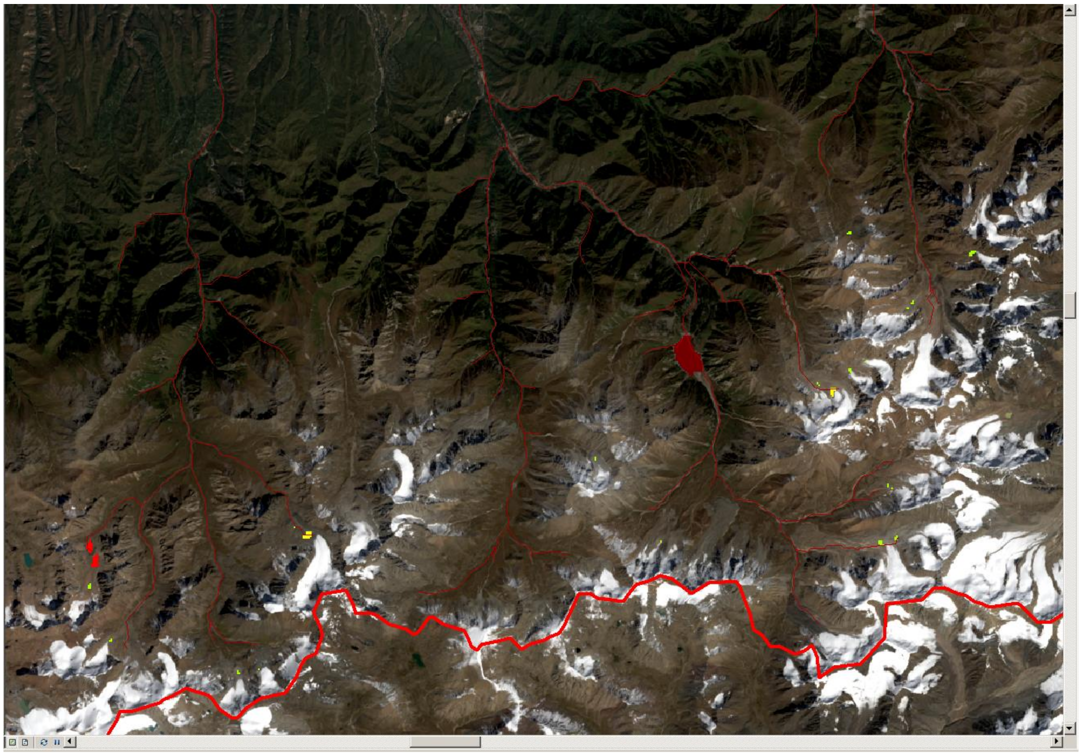

Figure 9 Mapping of glacial lakes located in catchment area of rivers that belong to Almaty (screenshot)

6.1.2 Active on-site activities

On-site prevention activities are more effective in economic perspective rather than passive activities, but there are several obstacles: difficulties with reaching a lake and transition of necessary materials and machines; risk of inducing outburst; leading to permafrost melting; etc (Birzhanov *et al.* 1998).

Depending on type of glacial lake's dam on-site activities for decreasing level of water could be different. In case of ice - drilling of chink and tunnels; in case of soil with stones and permafrost – creation of channels and conducting of artificial dam breach could be implemented (Medeu 2011).

In 1964-1970 rapid increasing of water level in glacial lake №2 forced to conduct on-site prevention activities on decreasing water level. In that case were used siphons. This prevention works were stopped in 1970, and in 1973 there was an outburst of lake №2 that developed hazardous GLOF event described above (Birzhanov *et al.* 1998; Plehanov *et al.* 1975).

In 1975-1976 activities in lake №13 in Ulken Almaty valley were conducted. Building of channel in moraine dam was done by using explosives. This method destroyed natural structure of moraine dam and induced GLOF in 1977. After that in 6 meters above the lake №13 developed new lake with number 13a. The volume of lake №13a started to quickly increase, and surface area increased as well because of glacier tongue's melting. Because of that in 1980 it was decided to decrease level of water in that lake. It was successfully done, but time after time there were appeared several hollows. In 2006 there were 3 hollows with melted water with total volume of 70,000 m^3. In 2010 these lakes developed into one lake and water volume reached 140,000 m^3. In the same year was built water-evacuation channel and water volume was decreased to 40,000 m^3 (Medeu 2011; Esenov and Degovec 1979).

In 1977 water volume of glacial lake in Esik river basin, in Zharsai valley was reached 0.5 million m^3. In order to avoid the same GLOF as it was in 1963 on-site activities were needed. Building of channel was done, and 200,000 m^3 of water was spilled out. Unfortunately this activity triggered the melting of permafrost up to 30 m of thickness, and it caused outburst of the lake by underground tunnel. Since large amount of water was already spilled out scale of GLOF was relatively small (Yafyazova 2007; Birzhanov *et al.* 1998).

Since 1976 in the lake №6 were conducted several activities on decreasing level of water. This lake, located by glacier named after Manshuk Mametova, is one of the most vulnerable lakes with high level of danger (Blagovechshenskiy *et al.* 2015; Bolch *et al.* 2011). By using tarpaulin sheets were created open channel with length of 120 meters. Tarpaulin sheets were used in order to avoid dam erosion and water filtration into permafrost. Building of shutter provided ability to control the flow of water, so used method was successfully applied. In 1997-1998 the volume of the lake was about 200,000 m^3 and already developed technic was used to decrease water level to 110,000 m^3. According to the (Medeu 2011) in 2004 volume of water in the lake was 180,000 m^3, and in 2010 it reached 250,000 m^3. In that year the same approach was used, but in the same time siphons were also installed, so in the end water level was decreased up to 150,000 m^3 (Medeu 2011).

As we can see from cases in 1973 in Kishi Almaty valley, in 1977 in Ulken Almaty valley, and in 1977in Zharsai valley on-site activities on decreasing water level by discharging it though built channels were unsuccessful, and triggered GLOFs. The main reason of it was that geological structure of the moraine dam and thermodynamic processes between dam-lake-glacier were not fully studied. Erosion of moraine dam, water filtration into dam, melting of permafrost because of direct contact with water and because of surface layer loss, as well as other processes were not taken into account as an outflow. However, after these unsuccessful accidents several improvements came up and during the on-site works in glacial lake №6 all geological and hydrological factors were studied and were taken into consideration. Experiences received during the previous years helped to develop successful method. The same situation occurred with passive activities as well. However, building of large dams is very expensive. On-site preventive actions are more effective not only economically but also ecologically, because GLOFs have negative impact to the natural landscape and vegetation of a valley as well. So development of on-site preventive activities by using new technologies is needed.

6.1.3 Passive activities

Building of protection dams from mudflow started in 19^{th} century. In 1921 mudflow triggered by rainfall destroyed eastern part of Almaty city and killed about 500 people. Since that time it was clear that city have to be protected, and several approaches were used in order to reach this mission. In that period of time experiences on mudflows triggered by GLOFs were very poor, and year after year with different hazardous events disaster management plan of the city was improved several times. In 1964-1966 in Kishi Almaty river basin were built 4 protecting metal constructions, gabion dam (busked dam) in upper part of the valley called as Mynzhylky, and also siphon spillway that helps to decrease water level. Metal constructions were weak and had no ability to catch heavy mass of mud. Because of that were developed new projects, and one of the biggest and one of the most important of them was building of Medeu dam (Figure 10). Building of Medeu dam was started in 1969 and finished in 1973. Height of this rock-fill dam was 110 m, and volume was 6.2 million m^3. GLOF and developed mudflow in 1973 destroyed 18 m gabion dam in Mynzhylky, and metal construction near resort 'Gorelnik'. Medeu dam cached 5.5 million m^3 of mud, but since dam was not fully completed, water was not spilled out, and quick filtration of water through dam walls could develop new outburst with higher volume. Only hard work of several institutes helped to solve this problem. After this event water catchment and spillway sections were built, height of the dam was increased up to 150 m, and volume reached 12.6 million m^3 (Yafyazova 2007; Birzhanov *et al.* 1998; Medeu 2011).

Figure 10 Medeu dam located in Kishi Almaty valley. Photo credits to: (Medeu 2011)

After GLOF in 1977 building of a dam in Ulken Almaty valley was needed. Steel-concreate dam with height of 40 m and volume of 14.6 million m^3 was built in that valley after disaster (Figure 11). This dam has water-collecting constructions that provide automatic spill of water mass.

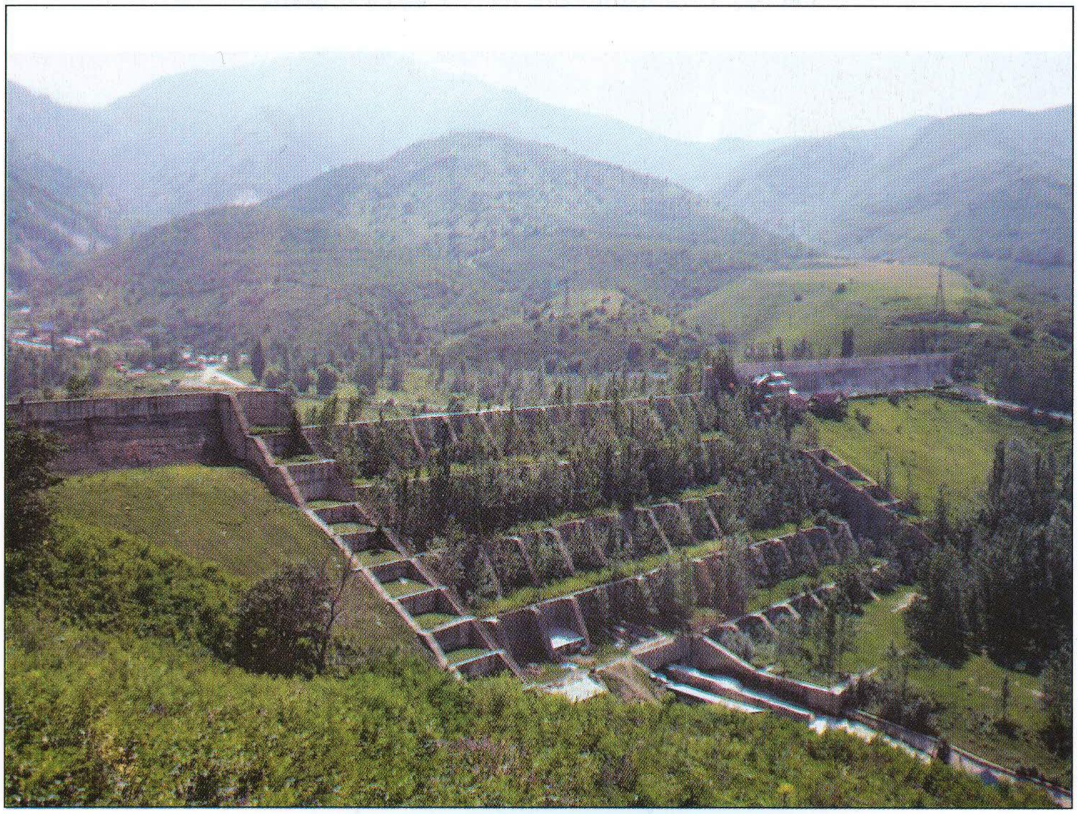

Figure 11 Steel-concreate dam in Ulken Almaty valley. Photo credits to: (Medeu 2011)

Metal constructions with large holes against mudflow were unsuccessful because in theory they had to catch big stones and large masses by filtration principles but in the end holes were chock-full and whole masses of mud-stone were collected there, and because of big disproportion of masses metal constructions were destroyed (Figure 12). Gabion dams were also unsuccessful against GLOFs, and only large reinforced concreate dams with water catchment system were able to protect the city.

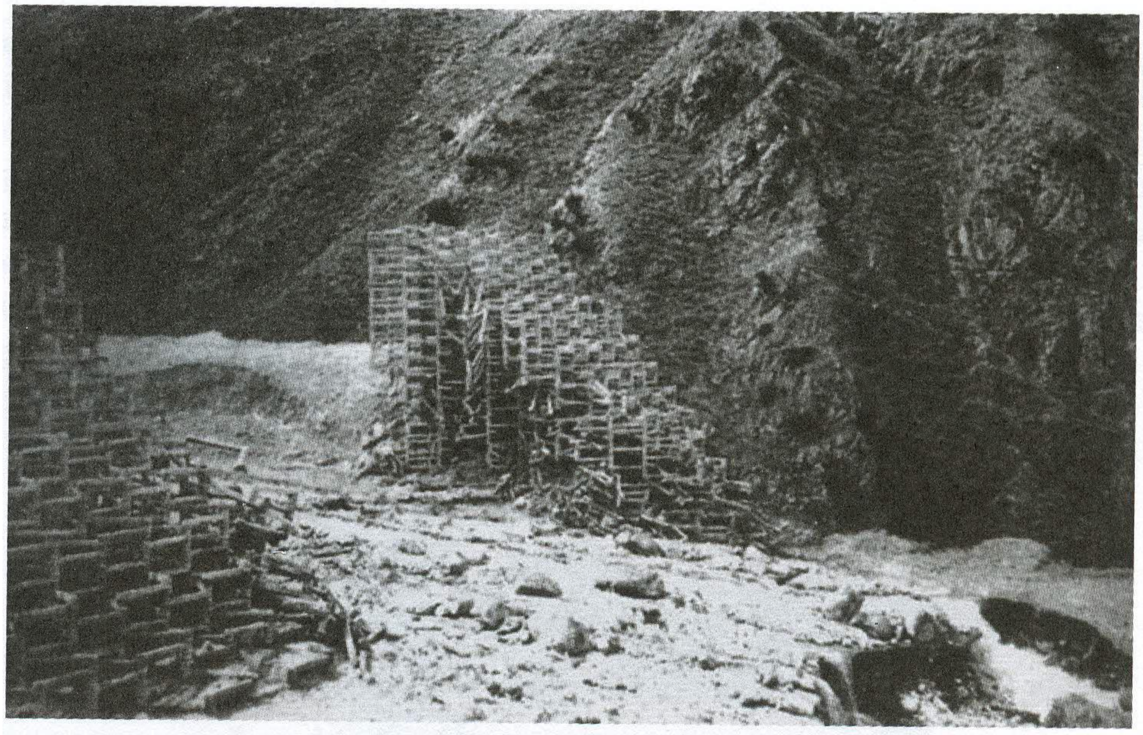

Figure 12 Destroyed anti-mudflow dam with large holes. Photo credits to: (Birzhanov et al. 1998)

Absence of significant GLOFs after 2000 show us that anti-mudflow activities works well, but GLOF in 2015 lead to doubts regarding to the safety of settlements. Outburst of glacial lake located near Kargalinka glacier was unexpected. GLOF happened during the night and residents of the city were not informed in time. The protection dam in Kargalinka river couldn't catch the whole mass of mud-stone and nearby areas were affected.

As it was seen most of the dams were built in 70s and 80s of last century. GLOF events were not well studied on that time, and scale of mudflows triggered by outburst of glacial lake was unclear, calculations were uncertain. Since that time number of glacial lakes and volume of already existed lakes decreased. It can be seen on example of lake №13a. Number of glacial lakes in Ile Alatau in 1970s was about 50, nowadays there is around 150 glacial lakes in that mountain range. All of that means that capacity of protective dams could be not enough to protect the city from GLOFs that could happen nowadays and in the future. Yafyazova (2007) also mentioned that volume capacity of protective dams much lower than needed. Outburst of glacial lake could develop mudflow volume of which could be much higher than volume of discharged water. Volume of lake, that outburst in 1956 and triggered mudflow with volume of 1.1 million m^3 was 32,000 m^3; in 1973 mudflow with volume of 3.8 million m^3 was triggered by lake with water volume of 260,000 m^3.

Glacial lakes identified during this research were classified according to their volume. Medeu dam located in Kishi Almaty valley have capacity of 12.6 million m^3, which means that volume of glacial lake located in the upper valley should be lower than ~400,000 m^3. In this valley were identified 4 lakes, and 2 of them have a volume more than 100,000 m^3. Protective dam in Ulken Almaty river basin has capacity volume of 14.5 million m^3. 4 glacial lakes from 9 identified in this valley have a volume more than 100,000 m^3.

6.1.5 Emergency response of state in case of GLOF in 2015

GLOF in 2015 was unexpected and one of the most significant glacial hazards in Ile Alatau mountain range since Kazakhstan got independence. Scale of this GLOF was not as big as previous GLOFs in Kishi and Ulken Almaty river basins, but several districts were affected, and this situation helped to examine activities of related institutions in emergency situation. During this research work several sources of social media was overviewed ("zakon.kz" 2017; "caravan.kz" 2017; "kapital.kz" 2017; "Informburo.kz" 2017; "FloodList" 2015) and information about actions of government was collected; chronology based on media sources was conducted.

Chronology of Glacier Lake Outburst Flood happened in 23rd of July, 2015:

Around 3 a.m. outburst of unnamed glacial lake, located by Kargalinka glacier, was happened. Around 3:10 a.m. people started to share information about mudflow in social networks, and according to them houses were damaged, cars were washed away, roads were filled up, and stream of water was increasing. Department of Emergency Situations of Almaty area was involved.

Around 6:30 a.m. deputy chief of Department of Emergency Situations of Almaty, Colonel E. Nurpeisov informed media that at 3 a.m. mudflow affected villages Kargaly and Kamenka. "Mudflow was caught by protective dam, and water discharge was carried out from two sluices. Dam is whole, and there is no threat to the city. In Nauryzbai batyr district's building of government was created support center for victims".

Around 7 a.m. adviser of city's akim (mayor) S. Kuyanov informed that at 5 a.m. akim (mayor) of the city and other hydrologist professionals did flight by helicopter in order to assess affected territory.

Around 9 a.m. S. Kuyanov informed that Karagaily and Tausamaly micro-districts were affected by mudflow. The second support center was created at school №176. Evacuation of people from affected areas was going on, and 200 people had been already evacuated. Department of Emergency Situations of Almaty city, Department of Internal Affairs of the city, Ministry of Internal Affairs of Kazakhstan Republic, Rescue service, Medical service, and other state institutions, totally 885 people and 150 pieces of machines were involved.

Around midday hot line for affected residents was created; bank accounts and support lines for donations were created as well. 2 billion Tenge (around 10 million US dollars) was allocated from government to support all activities and to help affected residents. 898 people were evacuated.

Afternoon 'Kazselzashita' informed that volume of glacial lake was 40,000 m^3; distance between lake and protective dam was 3 km; dam caught 20-30 thousand cubic meters of debris flow, and it was about 10% of dam capacity. Capacity volume of protective dam is 220,000 m^3.

Around 6 p.m. head of hospital №7 informed that 5 people were hospitalized. Vice ministry of Internal Affairs V. Bozhko informed that monitoring of all moraine dammed glacial lakes was going on by three helicopters. Siphons in lake №6 was used in order to decrease water level in dangerous lake. Unnamed lake outburst because of extremely hot weather – glacier mass that was kept water melted down, and underground channel was occurred.

To the support point in school №176 327 people were delivered, 78 of them asked for medical support. 127 private houses were affected in Algabas micro-district, 2 schools were affected in Nauryzbai district.

In 24th of July 2015 representative of Ministry of Internal Affairs informed that 1763 people were currently worked on affected areas; 711 people in Nauryzbai district and 408 people in Alatau district were evacuated.

In 25th of July situation was stabilized. GLOF destroyed 7 bridges, 27 posts of electricity lines, and damaged gas pipe lines. 3,000 people had no access to electricity, 1036 people were evacuated. 1800 people, 308 pieces of machines, 3 helicopters were involved to solve emergency situation. About 5,000 m^3 mud-stone mass was taken out from residential area.

This case basically shows us the ability of state institutions to deal with emergency situations. Government of the city did great job on solving emergency situation and on supporting residents of affected areas. Experience from last century had own impact and a fact that GLOF in 2015 was the most significant accident in last 30 years means that preventive on-site activities have been done well. Glacial lake №6 in Kishi Almaty valley could be a nice example of that. However, GLOF in 2015 also present several mistakes that have to be improved. Breach of unnamed lake was unexpected, which means that methodology of identification of potential dangerous glacial lakes should be revised. GLOF happened during the night, and people were not informed in time, which means that early alarming system did not operate. Mudflow mass was caught by protective dam, but residential area located lower from the dam was affected. Reason of that could be: sluices of the dam were quite big, and water flowed through them created secondary mudflow; or sluices were too big and some amount of mud-stone was transferred with water to residential area. Anyway, construction design of the dam should be assessed. Other problem is that vulnerable area was built up. A lot of houses were built there illegally, which means that urban planning was weak in different perspectives. Origin of these buildings were explained as because they use to be outside of the city, and joined to Almaty recently.

Conclusion

The main goal of research was to assess melting of Ile Alatau glaciers and corresponding threats to Almaty city. In order to achive this goal changes of glacier surface area from 1972 to 2016 was assessed by using Landsat images. Results showed decreasing of glacier surface area to 32.62% between 1972 and 2016. Analysis of data from meteorological station Mynzhylky it was seen that average year temperature in high mountain areas increased to ~0.7˚C. Amount of precipitation increased as well. Since middle of last century amount of precipitation was increased with speed of 1.6 mm/year, and in first 6 years of this century reached average amount of 898 mm. Temperature increased mostly in winter seasons, but precipitation mostly fell from August to April (78%). These factors were found as a main causes of glacier depletion in Ile Alatau.

Depletion of water resources and GLOF events were investigated as the main consequences of glacier depletion. Despite melting of large area of glaciers, percentage of melted glacier's water on river catchment was not significant (less than 20%). Hydrological circle of the region and availability of other fresh water resources as ground water was also taken into account, and finally, it was concluded that melting of glaciers does not have significant impact on local water resources yet. However, future scenarios of this process have to be assessed.

Analysis of past GLOF events and rapid development of glacial lakes (from 56 to 187 between 1972 and 2016) in Ile Alatau mountain range showed that melting of glacial lakes has direct impact on development of glacial lakes with danger of GLOF. Frequency and scale of past GLOF events proved that Northern Slope of Ile Alatau has high danger of GLOF events.

In order to examine safety of local settlement from GLOFs, disaster management plan of Almaty city and past preventive activities were analyzed. Absence of significant GLOF events in last 30 years showed that experience collected in 70s and 80s of last century helped to develop effective methods of on-site preventive activities. However, GLOF that happened in 2015 and comparison of glacial lake volume and capacity of protective dams showed that capacity, structure, and function of dams have to be assessed by taking into consideration rapid development of glacial lakes. On-site activities of responsible institutions as well as emergency response of state in case of GLOF were found well developed and very effective.

To be concluded, of Ile Alatau mountain range are melting because of raising of temperature. Tis process caused development of glacial lakes that have danger of GLOF for local settlements. However, effective anti-mudflow activities of responsible institutions are provide safety of local settlements. Despite to that, structure of dams and future development of glacial lakes have to be assessed.

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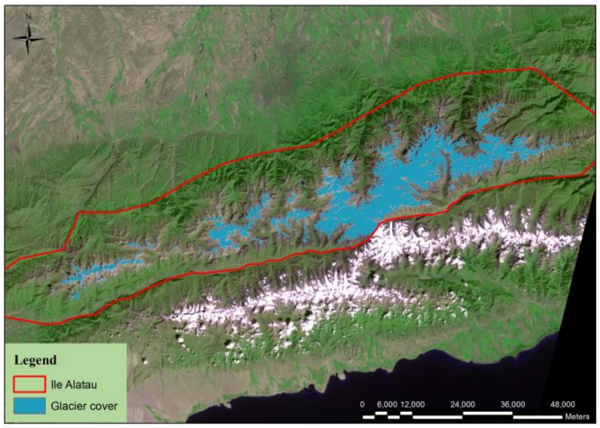
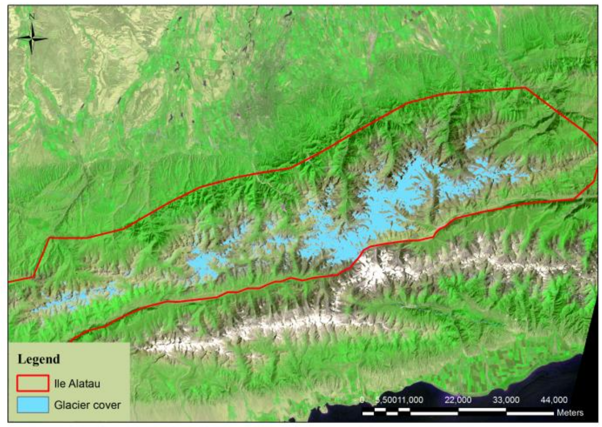
Appendices

Appendix 1 Maps of glacier surface area of Ile Alatau mountain range in 1972, 1978, 1990, 1999, 2007, and 2016

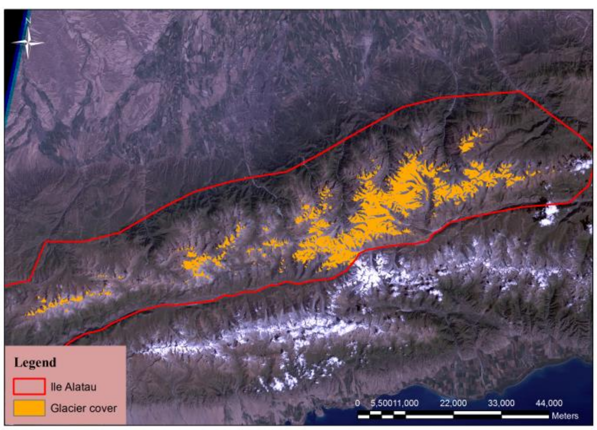
Glacier cover of Ile Alatau mountain range (07/Sep/1972)



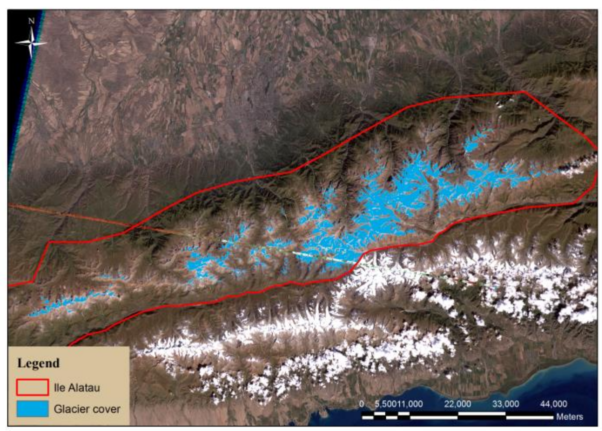
Glacier cover of Ile Alatau mountain range (29/Jul/1978)



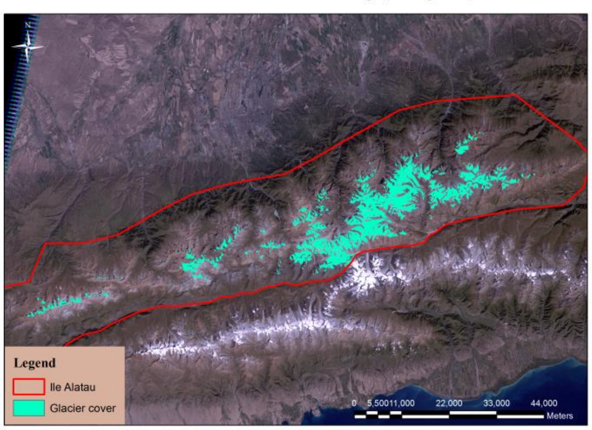
Glacier cover of Ile Alatau mountain range (07/Aug/1990)



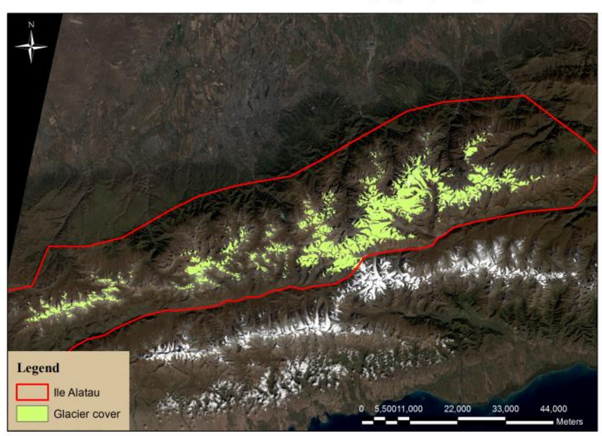
Glacier cover of Ile Alatau mountain range (09/Sep/1999)



Glacier cover of Ile Alatau mountain range (22/Aug/2007)

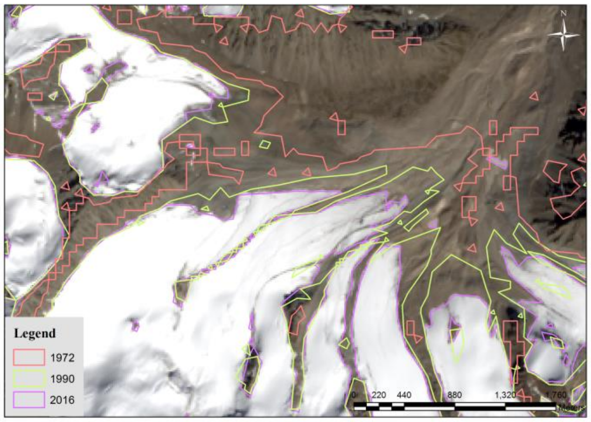


Glacier cover of Ile Alatau mountain range (15/Sep/2016)

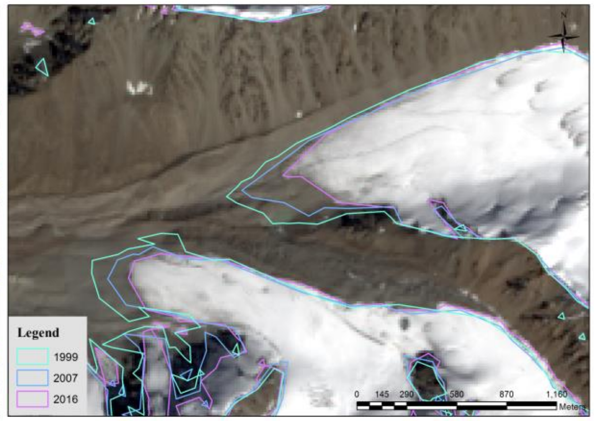


Appendix 2 Maps of changes of glacier surface area of Ile Alatau in different years

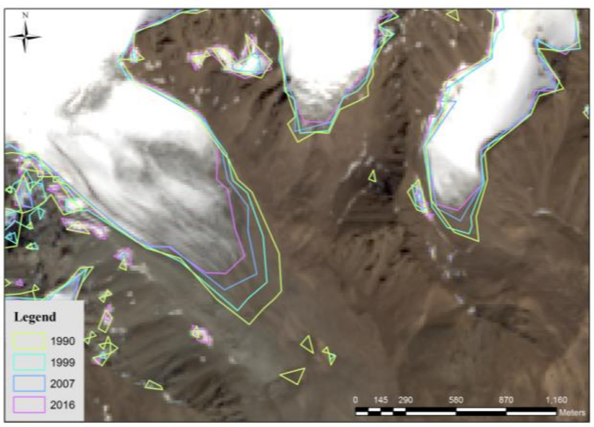
Changes of glacier surface area between 1972 and 2016 in Ile Alatau



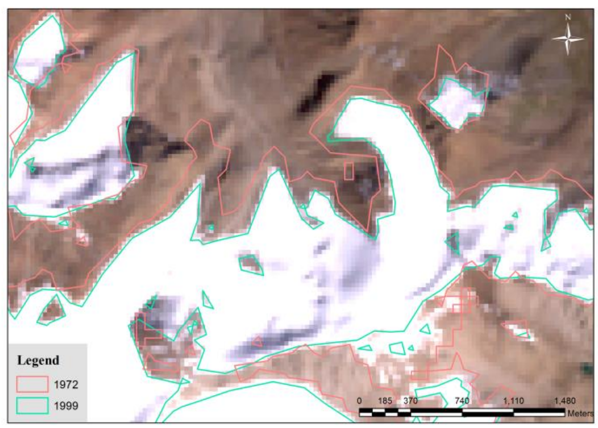
Changes of glacier surface area between 1999 and 2016 in Ile Alatau



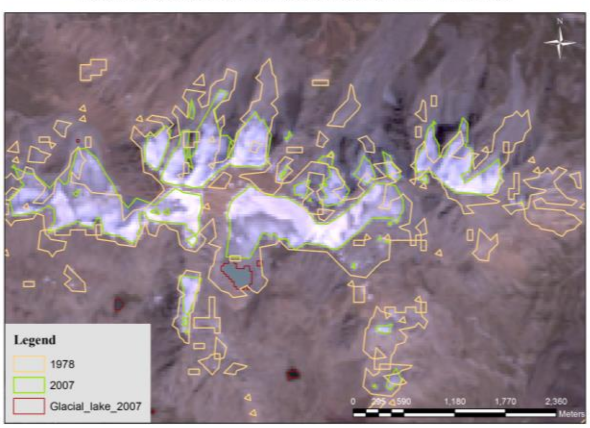
Changes of glacier surface area between 1990 and 2016 in Ile Alatau



Changes of glacier surface area between 1972 and 1999 in Ile Alatau

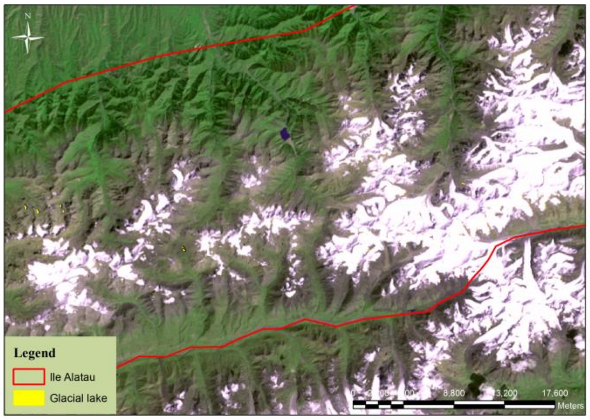


Changes of glacier surface area between 1978 and 2007 in Ile Alatau

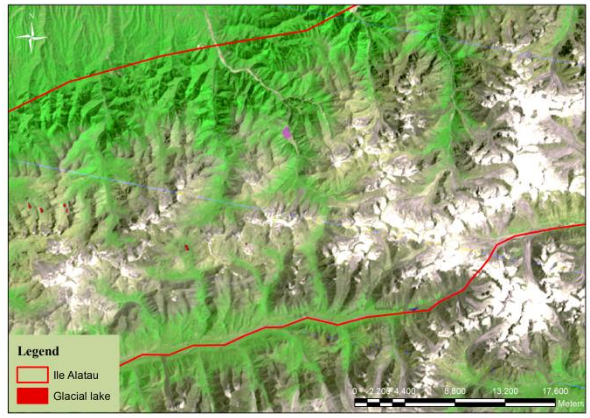


Appendix 3 Maps of glacial lakes of Ile Alatau mountain range in 1972, 1978, 1990, 1999, 2007, and 2016

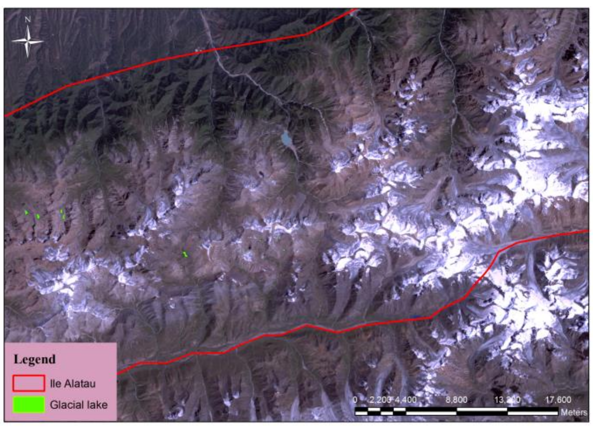
Glacial lakes in Ile Alatau mountain range (07/Sep/1972)



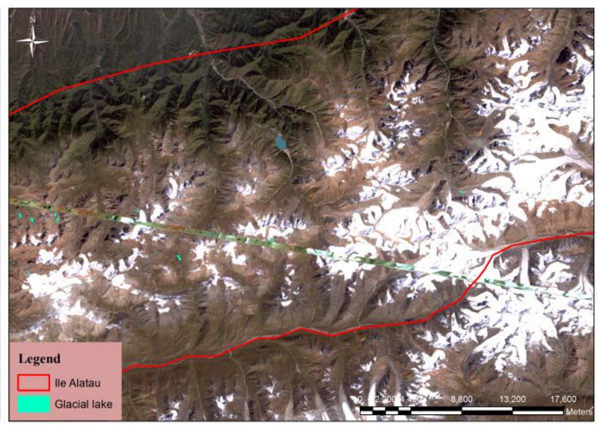
Glacial lakes in Ile Alatau mountain range (29/Jul/1978)



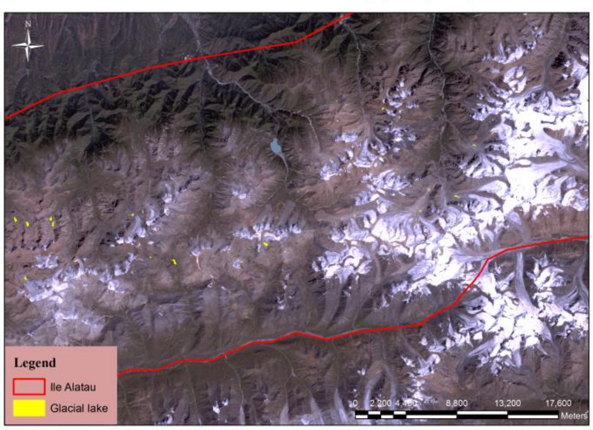
Glacial lakes in Ile Alatau mountain range (07/Aug/1990)



Glacial lakes in Ile Alatau mountain range (09/Sep/1999)



Glacial lakes in Ile Alatau mountain range (22/Aug/2007)



Glacial lakes in Ile Alatau mountain range (15/Sep/2016)