Synthesis report on GLOF hazard and risk in Kyrgyzstan

State of Knowledge

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Outline

1. Introduction

Central Asia is facing important challenges in view of coping with adverse effects of climate change. Like many other mountain regions worldwide, Central Asia is particularly sensitive to changes in global climate, from both a physical and societal perspective. The disappearance of mountain glaciers and thawing of permafrost are clear indicators of warming in a rapidly changing glacial and periglacial environments. As a direct consequence, the size and number of glacial lakes are increasing, and so too is the risk of Glacial Lake Outburst Floods (GLOFs), and glacial mudflows.

GLOFs refer to the sudden discharge of a water reservoir that has formed either underneath, at the side, in front, within, or on the surface of a glacier, and related dam structures can be composed of a mix of ice, moraine or bedrock. Some glacial lakes gradually enlarge over time at the front of the glacier, while other, non-stationary lakes can be more erratic, fluctuating in size over short time scales. The potentially high discharges and sediment content of GLOFs can devastate local lives and livelihoods. This is particularly true in rural, mountain communities, where socio-economically disadvantaged, indigenous groups, ethnic minorities, women, children and elderly are highly sensitive and particularly vulnerable to the impacts of climate change. However, the societal impacts of GLOFs can be far-reaching (>100 km) as a result of hazard transformations or chain reactions, such as damming of valleys, secondary outbursts and debris flows. As such, approaches to GLOF hazard and risk assessment must consider large spatial scales, often in a transboundary regional context.

Recognising this significant and increasing threat to the region, the UNESCO-led project “Reducing vulnerabilities of populations in the Central Asia region from glacier lake outburst floods in a changing climate” (GLOFCA), was initiated in 2021 under the Adaptation Fund. A key outcome of the GLOFCA project will be the establishment of four demonstrative GLOF Early Warning Systems (EWS) in selected pilot sites within Kazakhstan, Kyrgyzstan, Tajikistan, and Uzbekistan. In order to provide a robust scientific basis for the design and implementation of these Early Warning Systems, a comprehensive synthesis of the state of knowledge on GLOF hazard and risk is being undertaken for each country. As a series of 4 reports, each synthesis draws on the wealth of scientific information and data that has been gathered over many decades by national authorities and research institutions, complimented with international studies and perspectives.

The four national synthesis reports follow a common format. First, a synthesis of cryospheric change in the region is provided. This is followed by a comprehensive review of reported GLOF and mudflow disasters. Methodological approaches to lake mapping and monitoring are then outlined, and then finally, the methods, criteria, and classification schemes used to assess hazard and risk are presented.

2. Cryospheric change across Kyrgyzstan

2.1 Temperature and precipitation

Climatic and weather conditions on the territory of Kyrgyzstan are one of the main factors determining the formation of hazardous natural water processes. They are manifested through both regional and local synoptic processes, initiating the occurrence of floods, mudflows associated with glacial lake outburst floods (GLOF). Basic information on climatic parameters is provided by observations and measurements at meteorological stations (MS) of the Kyrgyz State Hydrometeorological Service (KSH), which has been constantly functioning since 1926.

There are series of observations for climatic parameters since 1881 (Karakol and Osh cities) and since 1885 (Naryn city). At present, the network of meteorological stations has been significantly reduced, however, hydrometeorological observations continue. There are a number of generalized works on the analysis of climatic conditions performed in previous years on the territory of the Republic (cf. Ryazantseva, Z.A. (1965); Ponomarenko, P.N. (1976); Scientific-Applied reference book on the Climate of the USSR (1989); Main Directorate of Geodesy and Cartography (1987))

In recent decades, based on data from Kyrgyzhydromet, an analysis of climate changes in the territory of Kyrgyzstan was carried out, which clearly indicates a widespread increase in the temperature of the surface air layer (e.g., fig.1), with a slight and ambiguous change in atmospheric precipitation in different regions of the country. Analysis of climatic changes (Third National Communication, 2016) for the four climatic provinces of Kyrgyzstan showed that the average annual air temperature for the period from 1885–2010 in the Kyrgyz Republic increased by 0.9 °C. For the period from 1927-28 to 2010, the air temperature increased in Northwestern Kyrgyzstan by 1.65°C, in Southwestern Kyrgyzstan by 2.14°C, in the Issyk-Kul basin by 1.04°C and in the Inner Tien Shan by 1.41°C. The greatest increase in average temperatures occurred in winter, while in summer, the average air temperatures remained almost unchanged. Atmospheric precipitation, in general, changed slightly, over the entire observation period, the amount of annual precipitation in the republic slightly increased (by 8-12%), and only at 2 stations - Suusamyr and Jalalabad, their steady decrease was noted.

The bulletins of the current state and climate change in Kyrgyzstan for individual years, issued by Kyrgyzhydromet, provide information on climate change since 1976. The rate of increase in the average annual air temperature in the territory of Kyrgyzstan reaches from 0.18°C/10 years for the period 1976-2014 (Annual Current Status Bulletin, 2015) to 0.22°C/10 years over the past 43 years (National report, 2020), which is slightly higher than the increase in the global temperature of the Earth over the same period (0.167°C/10 years). There is a prevailing tendency towards an increase in the annual precipitation by 1.8-2.9% in 10 years.

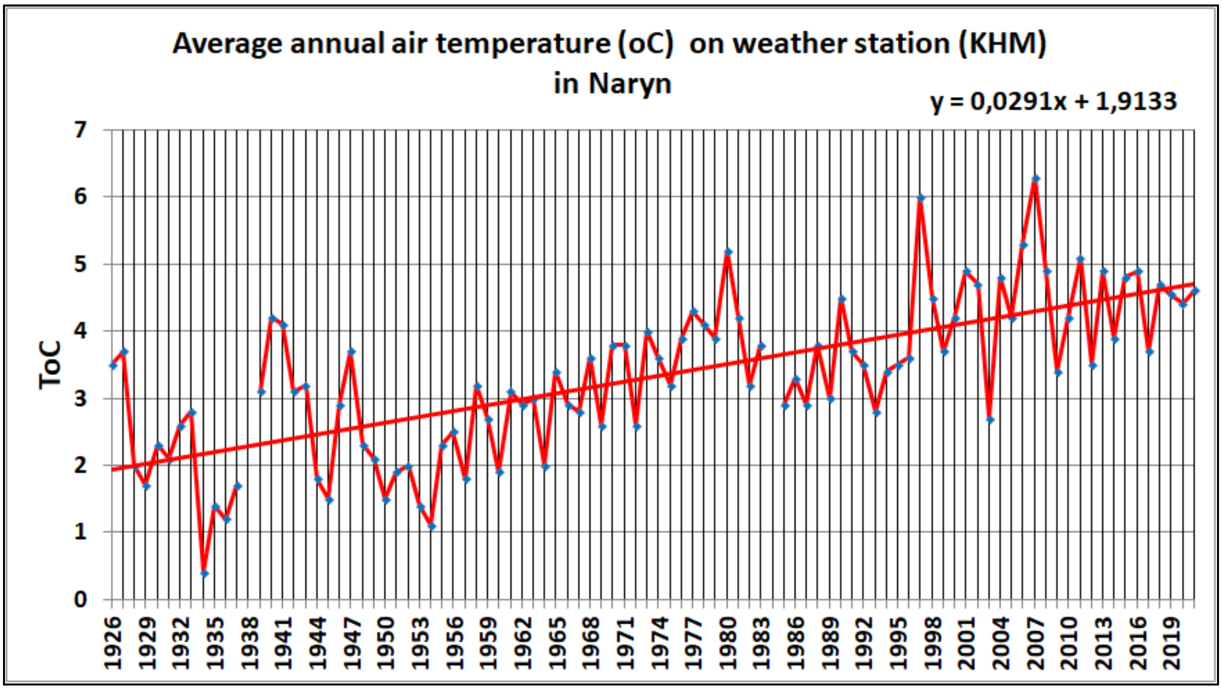

Fig.1: Change in the average annual temperature of the surface air layer at the meteorological station in the Naryn town from 1926 to 2021.

2.2 Snow cover

Increasing air temperatures and heterogeneously changing precipitation rates have led to diverging effects on the seasonal snow cover in the Tien Shan region (Sorg et al., 2012). For the total Tien Shan, maximum snow cover thickness has decreased by approximately 0.1 m and snow cover duration by 9 days, respectively, between 1940 and 1991 (Sorg et al., 2012). Sorg et al. (2012) find increases in maximum snow cover thickness and snow cover duration at all altitudes in western and central Tien Shan, but no visible trend in the northern Tien Shan for altitudes above 2000 m a.s.l. In contrast, Barandun et al. (2020) report an increase in snow depth for central Tien Shan. They attribute this to an increase in winter precipitation. Associated with the reduction in precipitation during the cold season (NDJF) there is a significant decrease in snow reserves for 2017-2021 (Mandychev, 2022). Currently, the analysis of snow cover changes on the territory of Kyrgyzstan is carried out at CAIAG according to the data of the Terra / MODIS satellite for forecasting river flow (Kalashnikova et al., 2017). In addition, it is possible to determine atmospheric precipitation, including during the cold period of the year, using satellite data from the Global Precipitation Measurement (GPM) mission.

2.3 Permafrost

Up to 34% of the territory of Kyrgyzstan is occupied by permafrost soil conditions (Usupaev et al., 2019). However, rapid warming has led to partial permafrost degradation in high mountain Central Asia (Marchenko et al., 2007). In the Tien Shan, permafrost temperature has experienced a continuous warming in the lower part of its altitudinal distribution zone since the 1950s leading to an average thickness increase of the active layer by 23% compared to the early 1970s (Marchenko et al., 2007). According to the results of model estimations, for the period 1880-2005, the altitude of the lower boundary of permafrost distribution increased by about 150-200 m, and the area of permafrost distribution in two river catchments of Malaya and Bolshaya Almaatinka in the northern Tien Shan (Ile Ala-Too Range) has decreased by approximately 18% (Marchenko et al., 2007).

2.4 Glaciers

The study of the glaciers of Kyrgyzstan has a long history, starting from 1859 to 1886 when expeditions were carried out, mainly of a explorative nature: Golubeva (1859), Venyukova (1860), Severtsova (1864, 1867, 1868, 1877 and 1878), Kaulbars (1869), Mushketova (1874-78), Mushketov (1880), Fetisov (1877-81), and Ignatiev (1886). Subsequently, in 1968-80s a Catalog of glaciers of the USSR, V.14.1968-80, was prepared and published based on the results of numerous researchers (e.g., Davydov & Korzhenevsky (1927), Palgov (1928-30), Kalesnik (1932-33), Avsyuk (1945-48), Bondarev & Zabirov (1964), Abirov et al. (1980)), as well as on the basis of the state topographic survey of the entire territory of Kyrgyzstan and aerial photography. This catalogue covers the whole Kyrgyzstan and contains information on the state of glaciers in the 40-70s of the twentieth century. The main patterns of functioning and characteristics of the glaciers of Kyrgyzstan were presented in the Atlas of the Kyrgyz SSR (1987). Subsequently, the change in the glaciers of Kyrgyzstan and their characteristics were studied by Dikikh (1982), Kuzmichenok (1986,88,2006), Aizen (1984), Kotlyakov (1993), Dyurgerov (1995), Maksimov (1995), Kutuzov (2009), Usubaliev et al. (2009,2017,2019), Osmonov (2014,2018), Kenzhebaev (2019), Mandychev (2017) and Shabunin (2018).

General characteristics of glaciers and the glacial system of Kyrgyzstan are descibed in the Atlas of the Kyrgyz SSR (1987). Median glacier elevations in the Tien Shan range from 3700 to 4200 m a.s.l. and are highest in the central part (Barandun et al., 2020). Most glaciers in the Tien Shan range are polythermal glaciers (Barandun et al., 2020). According to the satellite based Kyrgyz glacier inventory Catalogue from 2018, 9’959 glaciers occupied about 3.3% of Kyrgyzstan, with a total area of 6’683.9 km2 and the total number of glaciers between 2013-2016 (Shabunin, 2018). Comparison of glacier parameters obtained as a result of the above inventory with data on glaciers from the Catalogue of Glaciers of the USSR (40-70s of the twentieth century), showed that over, about 70 years, there was a decrease in the area of glaciers of Kyrgyzstan on average by 16% or 0.23%/year. The most pronounced reduction occurred on the peripheral ridges, and especially those with lower elevation (Sorg et al., 2012), for example, in the Talas basin by 47% and in the Chui basin by 28%. The number of glaciers has increased over the same time, due to the collapse of larger glaciers and their transformation into several smaller galciers. The total volume of water in the glaciers of Kyrgyzstan was previously estimated at 650 km^3 of water (Dikikh & Usubaliev, 2009; Usupaev et al., 2019). Taking into account an glacier area reduction of 16%, it can be assumed that the volume of glaciers has also decreased by this amount and is currently close to 546 km^3. Table 1 presents values for glacier mass and area loss based on the results of different studies carried out in Kyrgyzstan. In the mid-1970s, glacier wasting accelerated in the outer and inner Tien Shan ranges (Sorg et al., 2012). Most Central Asian glacier change studies highlight a complex and heterogeneous response to the changing climate. Barandun et al. (2020) suggest that this may be related to the presence of surging glacier and strongly debris covered glaciers in Central Asia. Narama et al. (2010) found the most dramatic glacier retreat in the outer ranges of the Tien Shan. Farinotti et al. (2015) estimate the overall decrease in total glacier area and mass for the Tien Shan from 1961-2012 to be 18±6% and 27±15%, respectively. Between the 1970’s and the early 21st century, annual area shrinkage was between 0.26% and 0.63% in the mountain areas of the Kyrgyz republic. The highest values were found for the Pskem region in western Kyrgyzstan followed by some valleys in the Ili Kungöy of the northern Tien Shan. Values for the central Tien Shan spread around 0.4% with the lowest values for the Terskey Ala-Too. Area loss rates in the Central Tien Shan increased strongly over the years from 0.12% yr^{-1} for 1943-1977 to 0.33% yr^{-1} for 1977-2003 and to 0.59 ± 0.34% yr^{-1} for 2003–2013 (Petrakov et al., 2016), and then to 0.93 ± 0.61% yr^{-1} for 2013-2018 (Barandun et al., 2020). Glaciers in the SE-Fergana region showed no decrease from 2000-2007 (Narama et al., 2010). Sorg et al. (2014) project that significant glacier wasting in the northern Tien Shan until the end of the 21st century will cause a loss of up to 2/3 (or 60%) of the 1955 glacier extent.

Table 1: Values for glacier mass and area loss in Kyrgyzstan.

Range	Region	Country	mass loss	area loss	Reference
	Tien Shan		27±15% (1961-2012)	18±6% (1961-2012)	(Farinotti et al., 2015)
	C Tien Shan		$-0.21 \pm 0.33{\times}10^3$ kg m^{-2} yr^{-1} (1961-2012)	0.12% yr^{-1} (1943-1977) 0.33% yr^{-1} (1977-2003) 0.93 ± 0.61% yr^{-1} (2013-2018)	(Farinotti et al., 2015) (Barandun et al., 2020)
	western KYR	KYR	$-0.60 \pm 0.47{\times}10^3$ kg m^{-2} yr^{-1} (1961-2012)		(Farinotti et al., 2015)
Pskem area	western KYR	KYR, UZB		19% (1970-2000)	(Narama, Kääb, et al., 2010)
Kyrgyz range (Ala Archa basin)	N Tien Shan	KYR		5.2% (1943-1977), 10.6% (1977-2003)	(Aizen et al., 2006)
Ile Ala-Too	N Tien Shan	KAZ		15% (1971-2007)	Chiyuki Narama et al., 2009)
Kungöy Ala-Too	N Tien Shan	KYR		12% (1970-2000) 15% (1971-2007)	(Narama, Kääb, et al., 2010) (Narama et al., 2009)
Kungöy (Chon-Aksu valley)	N Tien Shan	KYR		23.1% (1850-1955) 38.2% (1955-1999) 29.9% (1955-1979) 11.8% (1979-1999)	(Bolch, 2006)
Kungöy (Chon-Kemin valley)	N Tien Shan	KYR		13% (1850-1955) 16.4% (1955-1999) 7.8% (1955-1979) 9.3% (1979-1999)	(Bolch, 2006)
Terskey Ala-Too	N/C Tien Shan	KYR		8% (1971-2002)	(Narama et al., 2006)
eastern Terskey Ala-Too	N/C Tien Shan	KYR		19% (LIA-2003) 12.6% (1965-2003)	(Kutuzov & Shahgedanova, 2009)
Ak-Shiyrak	C Tien Shan	KYR		5.9 ± 3.4% (2003-2013)	(Petrakov et al., 2016)
Ak-Shiyrak	C Tien Shan, south to Terskey Ala-Too	KYR		4.2% (1943-1977) 8.7% (1977-2003)	(Aizen et al., 2006)
At-Bashy range	southern part of C Tien Shan	KYR		12% (1970-2000)	(Narama, Kääb, et al., 2010)
SE-Fergana	C Tien Shan	KYR		9% (1970-2000) 0% (2000-2007)	(Narama, Kääb, et al., 2010)

2.5 Runoff

About 70% of the central Asian water resources are located on the territory of Kyrgyzstan and Tajikistan (Zholdoshev et al., 2017), and >45% of all glaciers in Central Asia, that are a major source of nourishment for rivers, are located in Kyrgyzstan (Lipka, 2017). Therefore changes in glacier-fed streamflow regimes have direct implications on freshwater supply, irrigation and hydropower potential in Kyrgyzstan and other central Asian nations (Sorg et al., 2012).

The main patterns of river runoff and its typification on the territory of Kyrgyzstan are considered in the works of Shults (1965), Bolshakov (1974), the Atlas of the Kirghiz SSR (1987), and Mamatkanov et al. (2006).

Analysis of the cyclicity of river flow changes in Kyrgyzstan, located in different climatic zones, shows a stable increase in river flow from 1993 to 2019, while the previous observation period (1940-1992) was characterized by a decrease in river water availability. In the intra-annual distribution of river runoff for the same comparative periods, there is an increase in the volume of runoff during the months of seasonal snowmelt (MAMJ) and a decrease in the months of glacier melt (JAS) (Bobushev & Kalashnikova, 2017, 2021) (cf. **fig. 2**). The average annual runoff of the studied rivers for the period 1993-2019 increased by 107-135% compared to the values for 1939-1992.

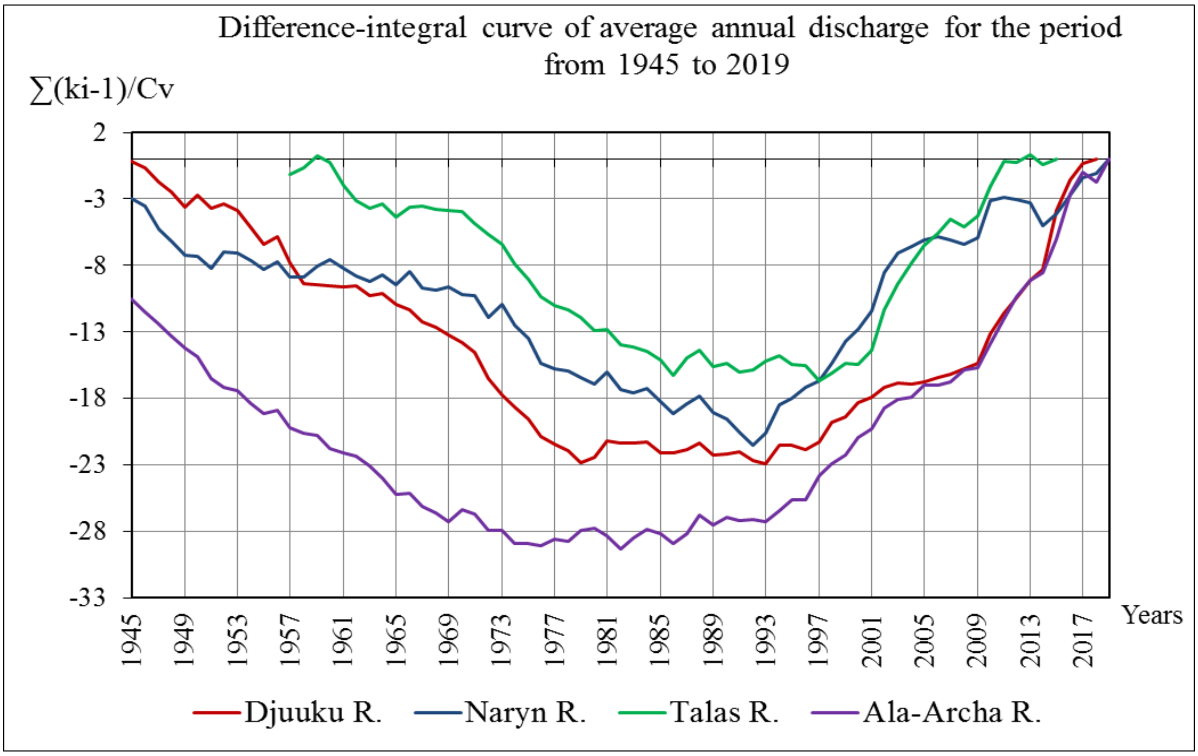

Fig.2: Difference-integral curve of annual discharge from 1945 to 2019 for the rivers Djuuku, Naryn, Talas and Ala-Archa in Kyrgyzstan.

Average annual runoff in Kyrgyzstan increased from 47.1 km^3 (1947–1972) to 50 km^3 (1973–2000) (Sorg et al., 2012). However, glacier melt water contribution in Central Asia will reach its peak in the next few decades (Duethmann et al., 2015). Additionally, climate warming will cause snowmelt to occur early in the spring months (Xenarios et al., 2018) and solid precipitation to decrease in spring and early summer (Sorg et al., 2012). Shifts of seasonal runoff maxima have already been observed in some rivers, and it is suggested that summer runoff will further decrease in these rivers if precipitation and discharge from thawing permafrost bodies do not compensate sufficiently for water shortfalls (Sorg et al., 2012). Continuing climate change will lead to more frequent flood hazards in spring and a shift of peak runoff from July to June (Xenarios et al., 2018). And a decrease in runoff, at least during the summer months, can thus be expected by the end of the 21st century (Sorg et al., 2012), potentially threatening water security in dry summers in areas like Bishkek – the densely populated capital of Kyrgyzstan (Sorg et al., 2014).

At present, a method for forecasting water availability for the growing season with a long lead time of 180 days (Kalashnikova et al., 2015-2017) has been tested and is widely used based on TERRA / MODIS satellite images, which provide information on the area of snow cover. Snow cover information is also used to predict the water availability of rivers for a shorter observation period - for months and decades, and is also a good tool that is freely available (Kalashnikova et al., 2018-2021). Methods for forecasting the water availability of rivers using MODIS imagery data have been tested not only on the Tien Shan rivers, but also on the high mountain river basins of the Pamirs (Niyazov et al., 2019, 2020). With the help of the MODSNOW program with a user-friendly interface information on the snow cover area as a percentage of the river basin area for some large river basins in Kyrgyzstan and Tajikistan has been developed (Gafurov et al., 2019). Qualitative and reliable forecasts of water availability contribute to timely prevention of expected high water, when preventive measures on protection against mudflows should be taken.

2.6 Glacier lakes

The first hazardous lake inventory for Kyrgyzstan, along with improved hazardous lake classification was developed in 1988 by Erokhin S.A. (Erokhin, 2012). Afterwards the dataset has been systematically compiled and updated with new data, and at present the dataset serves as an important tool for development of outburst flood and debris flow protection system.

In Central Asia glacier lake volume increased by about 20% between 1990-2019 (Shugar et al., 2020). Between 2000-2018, the number of lakes has doubled in the Terskey range, but stayed more or less the same in the Kungöy range (M. A. Daiyrov et al., 2019). According to (Bolch et al., 2011), in the north Tien Shan (Ile Ala-Too and Kungöy Ala-Too) 66 lakes were identified in the imagery of 1972, and 132 in 2007. The number of the lakes almost doubled between 1972 and 2000 while it remained nearly constant between 2000 and 2007. In the Adygene moraine-glacial complex in the Ala-Archa river catchment of the Kyrgyz range, eight new lakes appeared between 1960 and 2017 (V. Zaginaev, Erokhin, et al., 2019). The trend of increasing number and volume of glacier lakes is expected to continue in a warming world (Shugar et al., 2020). (Thurmann, 2011) (bzw. 2nd national communication) project an increase of likelihood of GLOFs for the Fergana valley and a decrease for the central and northern regions of Kyrgyzstan.

In contrast, the number of short-lived glacial lakes contained by blocked ice tunnels in the northern Tien Shan varies strongly (M. Daiyrov et al., 2018). Changes in number and volume are not directly related to short-term summer temperature anomaly, nor to precipitation or glacier recession, but rather to the regional geomorphological conditions (M. Daiyrov et al., 2018).

An activation of thermokarst processes weakening the stability of lake dams is observed for almost all high-mountain lakes on the northern slope of the Kyrgyz ridge (V. Zaginaev, Erokhin, et al., 2019).

Related climate warming, outbursts from lake Merzbacher have shifted from October to last third of July and first third of August since the 1930s (Xie et al., 2013, Bormudoi et al., 2012).

A development for many glacier complexes in the region of northern Tien-Shan is expected, runoff peak occurring at present or near future, gradual melting of buried ice, and formation of new potential hazardous lakes (Falatkova et al., 2019).

3. Glacier lake outburst floods (GLOF) and glacial mudflow disasters in Kyrgyzstan

Mudflows and floods are among the most dangerous natural hazards in Kyrgyzstan (State Agency for Environment Protection and Forestry & United Nations Environment Programme, 2016). Floods accounted for 48% of all registered natural disasters in Central Asia during 1990-2011 (ESCAP, 2012). They are mainly caused by extreme precipitation, by snow and ice melt and by GLOFs (ESCAP, 2012). Landslides affect 47% of Kyrgyzstan (ESCAP, 2012) and most of the country is exposed to flash floods and mudflows (Thurmann, 2011). There are 3103 rivers in Kyrgyzstan that are prone to mudflows (State Agency for Environment Protection and Forestry & United Nations Environment Programme, 2016). 1153 settlements, mainly in the Fergana valley, the Chu valley (leading to Bishkek and Tokmak), the Talas valley, and parts of the Issyk-Kul province (including Karakol) are exposed to flash floods and mudflows after heavy rainfalls (Thurmann, 2011).

One of the main factors in the risk of mudflows and floods are glacial mountain lakes (Zaginaev, et al., 2019; ESCAP, 2012). The Tien Shan has been experiencing frequent GLOF and debris flow activity since the 19th century (V. Zaginaev, Petrakov, et al., 2019). Regular study of GLOFs in Kyrgyz Republic began in 1966, after the catastrophic outburst of Yashilkul landslide dammed lake in the Isfayramsay river basin on the northern slope of the Alay range in 1966 (Kattel et al., 2020). Since 1952 more than 70 disastrous GLOFs have been registered in Kyrgyzstan (Janský et al., 2009). Between 1990 and 2008 around 850 flash flood and mudflow events were registered, with an additional 92 for the first 9 months of 2009 (Thurmann, 2011). Since the beginning of the 21^{st} century, mudflows and floods caused 70 emergencies annually (Lipka, 2017). Zaginaev et al. (2019) state that according to the Kyrgyz Ministry of Emergency, more than 1200 debris flows and floods have been recorded in Kyrgyzstan since 2000. They find that GLOFs and debris flow events occurred more frequently during the 1930s, 1960s and 1990s, as compared to other periods. This coincides with phases of glacier stagnation or even slight glacier advances, which, as they argue, may have led to increased ice flow velocity causing blockages of englacial or subglacial channels.

3.1 Process types

Landslides and mudflows in Kyrgyzstan are mainly caused by extreme precipitation, floods and GLOFs (ESCAP, 2012). Floods and mudflows are most common from April to May, but they also occur in summer (Thurmann, 2011). Most GLOF events recorded in Kyrgyzstan have been linked to the degradation of moraine-glacier complexes (Janský et al., 2010; Usubaliev & Erokhin, 2007). In the northern Tien Shan erosion and debris flow activity has been found to be high where unconsolidated debris is largely available (V. Zaginaev, Petrakov, et al., 2019). This availability is related to a large extent to the process of moraine-glacier complex formation (V. Zaginaev, Petrakov, et al., 2019). The drainage of glacial lakes often transition from a water flood to a debris flow (and back). This is because of debris entrainment that can add a considerable amount of deposits to the initial drainage volume (Narama et al., 2018).

Glacial lakes form in different contexts their outburst can be caused by different triggers. They can be differentiated by their location, their dam type, and their drainage process. Classifications that cover all the variety of types of mountain lakes have been developed In Kyrgyzstan. Only 20-30% of the total number of lakes at a certain stage of their development become outburst-prone. They have unstable dams, consisting either of moraine-glacial formations, or of loose weakly connected landslide-rockfall deposits. Such dams can collapse under the influence of a number of factors. In this case, outbursts of lakes occur, which are often accompanied by disastrous consequences for the inhabitants of downstream valleys and plains.

Classification of hazardous mountain lakes used by researchers in Kyrgyzstan was developed by Erokhin S.A. based on experience of Soviet researchers and own geological experience. For the classification of mountain lakes from the point of their outburst and mudflow hazard, geological factors of their formation are used, namely the genesis of their dams, the peculiarities of the structure and composition of these dams. This classification approach makes it easier to assess the outburst hazard of mountain lakes during aerovisual and ground surveys. According to the genesis, nature of the structure and composition of their dams, the outburst-prone mountain lakes of Kyrgyzstan are divided into the following types: 1) glacial, 2) moraine-glacial, 3) moraine, 4) moraine-dammed, 5) landslide (fig. 3). Within some types there are subtypes of lakes, which differ from each other by the peculiarities of genesis of dams, morphology of lake baths, by feeding and flow conditions.

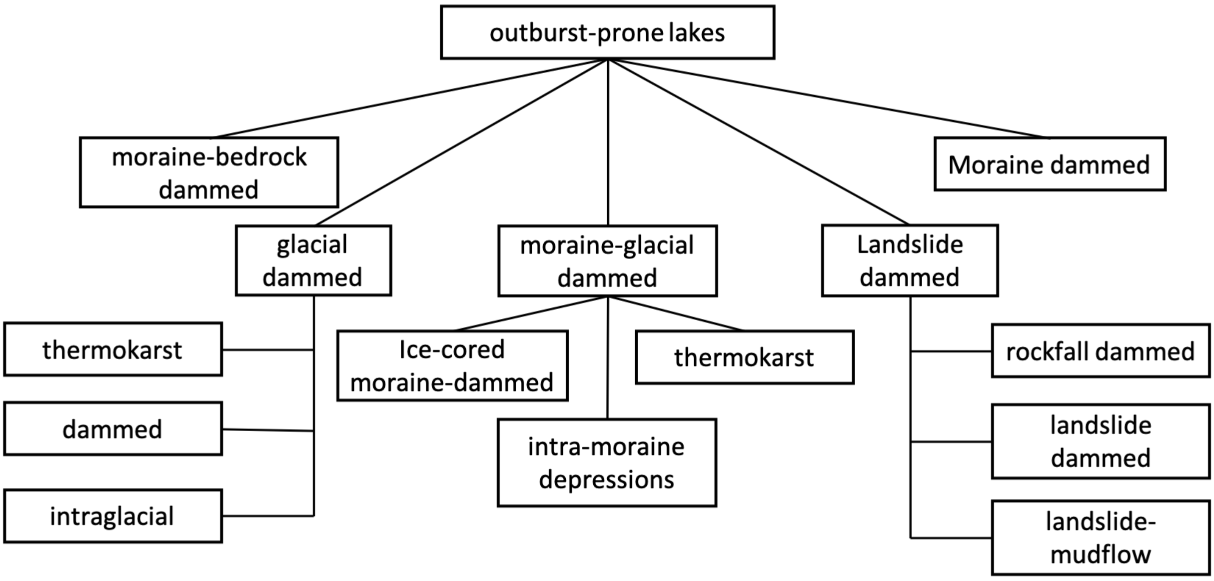

Fig. 3: Classification of hazardous mountain lakes in Kyrgyzstan (Erokhin & Zaginaev, 2020b). 'Moraine-glacial' refers to ice-cored moraine dammed.

Carrivick & Tweed (2016) analyze GLOFs all over the world. For Asia (including central Asia as well as the Himalayas) they find that >60% of GLOFs originate from ice dammed lakes and ~15% from moraine dammed lakes, while for the rest, the origin is unknown. In Kyrgyzstan mountain lake dams are of moraine-glacial type in 56%, of bedrock-dammed type in 21%, moraine-dammed type in 12%, landslide-dammed type in 10% and of ice-dammed type in 1% (Erokhin & Zaginaev, 2020b). As of 2018, 363 outburst prone lakes were registered for Kyrgyzstan (V. Zaginaev, Erokhin, et al., 2019). Most of them, namely 195, belong to the moraine-glacial type, 81 to the bedrock-dammed type, 46 to the moraine-dammed type, 38 to the landslide-dammed type, and 3 to the ice-dammed (V. Zaginaev, Erokhin, et al., 2019). For the Kyrgyz Ala-Too most glacial lakes form in intramorainic depressions (53.3%), followed by bedrock (and moraine) dams (18.9%), moraine-dams (14.5%), landslide dams (8.9%) and ice dams (4.4%) (Falatkova et al., 2018).

Concerning the dam type of glacial lakes, moraine-dammed lakes are considered the most dangerous type of lakes in Kyrgyzstan (Janský et al., 2009). The drainage of moraine-dammed lakes is often caused by a failure of the moraine dam (Narama et al., 2018). Concerning the drainage type of glacial lakes, lakes with subsurface drainage are considered to be the most hazardous type. This is because the timing of an outburst is hard to predict, since the knowledge of subsurface drainage functioning is still very limited (V. Zaginaev, Falatkova, et al., 2019). In the Kyrgyz Ala-Too 76.7% glacial lakes drain through the subsurface (Falatkova et al., 2018).

Ice-dammed lakes release water along lateral moraines or through the glacier itself. Ice channels can be closed due to ice deformation and lakes can fill up until the create another outlet creating a GLOF

(Mayer et al., 2008). Short-lived “tunnel-type” glacial lakes form when an ice tunnel gets blocked (e.g. through freezing or collapse). Such lakes can grow and drain (through opening of an ice tunnel) extremely quickly over the period of just a few months (Narama et al., 2018). The blockage and subsequent opening of ice tunnels can lead to repetitive growth-drain cycles. These lakes typically start forming in May, expand throughout the summer filled by ice and snow melt, and drain around the end of July and mid-August when ice tunnels reopen due to ice melting (Narama et al., 2018).

Most glacial lakes in the northern Tien Shan are either moraine-dammed lakes or supra-dead-ice lakes (Narama et al., 2009). However, In contrast to high mountain Asia (Himalaya) where moraine-dam failures are the most common GLOF processes, in Central Asia and Kyrgyzstan glacial lakes are often short-lived and develop over very short time periods (Narama et al., 2018). Many such lakes were found in the northern Tien Shan (M. Daiyrov et al., 2018), and especially in the western Teskey Range, recent large lake drainages have come from the tunnel-type of short-lived glacial lakes (Narama et al., 2018).

3.2 Known triggering and preconditioning factors

The triggering and preconditioning factors of lake drainage depend on the type of lake and dam, the nature of underground tunnels, the condition of dead ice in moraines, glacial water infiltration, etc. (M. A. Daiyrov et al., 2019). Some important factors for lake outbursts are high air and water temperature and high water level (intensity of filling) in the potential hazardous lakes (V. Zaginaev, Erokhin, et al., 2019). Climate warming leads to destabilization of moraines and hillslopes, which is of importance especially for lakes with moraine and moraine-ice dams. The accumulation of meltwater in glacial lakes, such as the one in the Aksay moraine-glacier complex, can lead to outburst due to built-up hydrostatic pressure and limited capacity of subsurface channels (V. Zaginaev, Falatkova, et al., 2019). Mudflow activity in mountain valleys largely depends on the process of moraine formation (Erokhin & Zaginaev, 2018). Moraine-glacier complexes can have a dampening effect on discharge. Zaginaev et al. (2019) suggest that moraine complexes are important features when it comes to debris flow and GLOF activity, and that they are more relevant than glacier shrinkage in northern Tien Shan. They show that for the northern Tien Shan, debris activity has been inversely correlated with glacier shrinkage from 1960 to 2017, and that the presence of rock glaciers substantially influences debris flow formation. They explain this finding by the fact that where glacier retreat is strongest, meltwater is forced to flow through ample amounts of debris contained in moraine-glacier complexes, which dampens discharge and inhibits the release of debris flow. They also suggest that an increase in glacier flow velocity (linked to stagnation or increases in glacier MB) can lead to the blockage of glacial channels and to subsequent GLOF events. Glacier behaviour strongly influences glacial lakes and vice versa (Mayer et al., 2008). In cases like the one of lake Merzbacher, when the lake grows, the glacier margin turns into a calving front. This creates a positive feedback between increasing mass loss into the lake and increasing ice velocities (Mayer et al., 2008). Mavlyudov (1997) proposes that the lake starts draining when part of the glacier becomes afloat. Xie et al. (2013) found that the ice covering on Lake Merzbacher has a close relationship with the outburst of the lake.

3.3 Past events

Mudflows have repeatedly emerged from the Teztor valley, a contributing valley of the Ala-Archa valley in the Kyrgyz Ala-Too located to the south of Bishkek in 1953, 1968, 1988, 2005, and 2012 (Zaginaev and Tuzova, 2013). Zaginaev et al. (2018) reconstructed 27 mudflows on the Aksay cone in the Ala-Archa valley between 1877 and 2015 using dendrochronological methods. Mudflow frequency was 0.25 yr^{-1} 1916-1960, then increased to 0.55 yr^{-1} in 1960-80, and dropped to 0.11 yr^{-1} in the most recent period of 1980-2015. 74 GLOF-debris flow events were reconstructed by Zaginaev et al. (2019) for 1874-2015 in the Ala-Archa (51) and the neighbouring Alamedin (23) valleys. In 1974, 1975, and 1980, large GLOFs occurred from a glacial lake at the Angisay glacier in the western Terskey Range of the Tien Shan mountains (Narama et al., 2018). During 2006 and 2014, four large GLOFs (all 100’000-450’000 m^3) occurred in the same range from several different lakes (Narama et al., 2018). In 1998, a catastrophic transboundary GLOF event occurred in the Alay Range of the Gissar-Alay region in the Pamir-Alay mountain system. The relatively small GLOF originated from the Kyrgyz Archa-Bashy lake and ended up being the deadliest GLOF in central Asia for the last 100 years (Petrakov et al., 2020). The ice-dammed lake Merzbacher, located in the forefield of the Northern Inylchek glacier in the central Tien Shan in the far western part of Kyrgyzstan, is blocked by the Southern Inylchek glacier and produces GLOFs periodically, usually at least once a year (Mayer et al., 2008). Some of the most important known GLOFs and glacial mudflows are listed in table 2.

Table 2: Compilation of some of the most important recent GLOFs and glacial mudflows in Kyrgyzstan.

Year	***Type***	***Lake name***	***Glacier name***	***River/valley***	***Mountain range***	***Region***	***Impacts***	***Reference***
1953	*GLOF*	*Teztor*	*Teztor*	*Teztor valley, → Ala-Archa river → Bishkek*	*Kyrgyz Ala-Too*	*N Tien Shan*		*(Erokhin et al., 2018) (Zaginaev and Tuzova, 2013)*
1960 1965 1968 1969	*Debris flow, GLOF*	*Aksay*	*Aksay*	*Aksay valley → Ala-Archa river → Bishkek*	*Kyrgyz Ala-Too*	*N Tien Shan*		*(Zaginaev et al.2016, Zaginaev and Tuzova, 2013)*
1974	*GLOF*		*Angisay*		*Terskey*	*southern shore of Issykkul*		*(Kubrushko and Staviskiy, 1978; Kubrushko and Shatravin, 1982)*
1975	*GLOF*		*Angisay*		*Terskey*	*southern shore of Issykkul*		*(Kubrushko and Staviskiy, 1978; Kubrushko and Shatravin, 1982)*
1978	*GLOF*	*Choktal*			*Kungöy Ala-Too*	*N Tien Shan*	*destruction of fields and roads; Chok-Tal village;*	*(Kubrushko and Staviskiy, 1978; Kubrushko and Shatravin, 1982)*
1980	*GLOF*		*Angisay*		*Terskey*	*southern shore of Issykkul*		*(Kubrushko and Staviskiy, 1978; Kubrushko and Shatravin, 1982)*
1988	*mudflow*			*Teztor valley, → Ala-Archa river → Bishkek*	*Kyrgyz Ala-Too*	*N Tien Shan*		*(Zaginaev and Tuzova, 2013)*
1998	*GLOF*	*Archa-Bashy*		*Shakhimardan catchment in the Fergana valley*	*Alay*	*Pamir-Alay mountain system*		*(Petrakov et al., 2020) (Narama et al., 2018) (V. Zaginaev, Petrakov, et al., 2019)*
2005	*mudflow*			*Teztor valley, → Ala-Archa river → Bishkek*	*Kyrgyz Ala-Too*	*N Tien Shan*		*(Zaginaev and Tuzova, 2013)*
2006	*GLOF*	*Kashkasuu*			*western Terskey*	*southern shore of Issykkul*		*(Narama et al., 2018)*
2008	*GLOF*	*western Zyndan*			*western Terskey*	*southern shore of Issykkul*		*(Narama, Duishonakunov, et al., 2010) (Janský et al., 2009)*
2012	*GLOF*			*Teztor valley, → Ala-Archa river → Bishkek*	*Kyrgyz Ala-Too*	*N Tien Shan*		*(Zaginaev and Tuzova, 2013)*
2013	*GLOF*	*Jeruy*			*western Terskey*	*southern shore of Issykkul*		*(Narama et al., 2018)*
2014	*GLOF*	*Karateke*			*western Terskey*	*southern shore of Issykkul*		*(Narama et al., 2018)*
2015	*GLOF*	*eastern Kurumdy*		*Aksay-Ton valley*		*southern shore of Issykkul*	*minor event*	*(V. Zaginaev, 2016)*

2015	*mudflow*	*Aksai*		*Ala-Archa valley*	*Kyrgyz Ala-Too*			*(Falatkova et al., 2018)*
?		*Koltor*			*Kyrgyz Ala-Too*	*N Tien Shan*		
1966		*Adygene*		*Adygene river → Ala-Archa river → Bishkek*	*Kyrgyz Ala-Too*	*N Tien Shan*		
2017	*GLOF*	*Chelektor*			*Kyrgyz Ala-too*	*Chuy region*		*(Falatkova et al., 2018)*

3.4 Impacts on society (losses and fatalities)

In the Northern Tien Shan region, GLOFs and debris flows pose a threat to settlements, including some of the major cities and towns (Narama et al., 2018). Mudflows led to 249 fatalities in Kyrgyzstan between 1990-2011. And mudflows and floods affected 68’161 and 10’623 people respectively and caused US$ 38 million and US$ 5 million damage respectively over the same time period (ESCAP, 2012). On average, every 10 years in Kyrgyzstan there are outbursts of relatively large alpine lakes, which cause great damage to the economy and claim human lives (Usupaev et al., 2019). The city of Bishkek was affected by a GLOF event in 1953 (Erokhin et al., 2018). The most destructive GLOF in Central Asia for the past 100 years was the Archa-Bashy GLOF in 1998. It caused more than 100 casualties in Shakhimardan village, an Uzbek exclave in the Ferghana valley (Narama et al., 2018; V. Zaginaev, Petrakov, et al., 2019). Four large GLOFs in the western Teskey range between 2006 and 2014 caused extensive damage, killing people and livestock as well as destroying property and crops (Narama et al., 2018). The event in 2006 damaged the mountain road and a bridge along the Uchemchek River (Narama et al., 2018). The 2008 outburst of west Zyndan glacial lake killed three people and many livestock, and it destroyed a bridge, a road, two houses, crops, and an important fish hatchery (Narama et al., 2018). The event in 2013 from lake Jeruy caused large damage to agriculture fields, irrigation infrastructure, roads, and many tombs (Narama et al., 2018). In 2014 only two bridges were destroyed (Narama et al., 2018). Large GLOFs from lake Merzbacher cause considerable infrastructure damage downstream (Mayer et al., 2008).

4. Lake mapping and monitoring

4.1 Mapping and monitoring process

Hazardous mountain lakes have been systematically studied in Kyrgyzstan since 1966 (Janský et al., 2009). There are several inventories reaching from rather big scale, for example the third pole (Zheng et al., 2021) or the Tien Shan (Wang et al., 2013), to medium scale, for example for the Kungöy Ala-too and the Teskey (Narama et al., 2009) (M. A. Daiyrov et al., 2019), for parts of the Kyrgyz range (Kattel et al., 2020), or for the Alay range (Mergili et al., 2013), and small scale, for example for the upper catchment of Syr Darya river (Zheng et al., 2019). Table 3 provides an overview of some relevant glacier lake mapping, inventorying and monitoring documents.

For the Kyrgyz territory, lakes which at different periods of their development were classified as outburst-prone lakes, are included in the catalog of outburst-prone lakes of Kyrgyzstan. The catalog is constantly updated with new data on lakes based on 1) ground surveys of lakes; 2) aerial observations; and 3) interpretation of space and aerial photographs. The catalogue is the basis for monitoring of outburst hazard of mountain lakes. **Figure 4** shows a map of the Kyrgyz territory indicating the locations and dam types of the lakes listed in the most recent catalogue of outburst-prone lakes compiled by authors from the Institute of Water Problems and Hydroenergy (Erokhin & Zaginaev, 2020b).

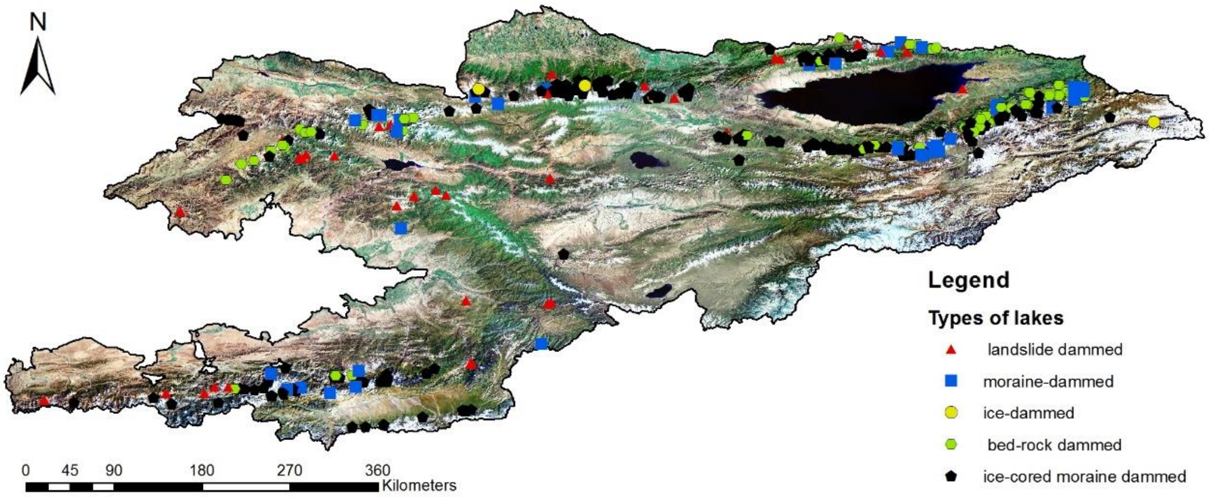

Figure 4: Map of the Kyrgyz territory with the location and dam type of all lakes mapped in the most recent lake catalogue of outburst-prone lakes in Kyrgyzstan compiled by authors from the Institute of Water Problems and Hydroenergy (Erokhin & Zaginaev, 2020b).

In 2009, more than 2000 alpine lakes of > 0.001 km^2 are reported for territory of Kyrgyzstan, 20% of which are potentially dangerous (Janský et al., 2009). In 2019 out of more than 3000 lakes in Kyrgyzstan, 372 lakes were included in the catalogue of outburst-hazardous lakes (Usupaev et al., 2019). 26 of them located in the region of Jalalabad, 170 in Issyk-Kul, 18 in Naryn, 65 in Osh and Batken, 21 in Talas, and 73 in Chui (Usupaev et al., 2019). According to the inventory developed at the Institute of Water Problems and Hydropower of the Kyrgyz National Academy of Sciences, there are at least 199 potentially dangerous lakes, most of which are of ice-cored moraine dammed type. In 2020 (Erokhin & Zaginaev, 2020b) report that of the several thousand mountain lakes in Kyrgyzstan, 374 are classified as hazardous. While 70-90% of all lakes have stable dams and are not expected to burst, 20-30% of the lakes have fragile dams that could potentially collapse (Erokhin & Zaginaev, 2020b). 38 lakes in Kyrgyzstan are dammed by landslides. 23 of them are located in the southern regions of Osh and Jalal-Abad, and 15 in the northern regions of Issyk-Kul, Naryn and Chuyskaya (Erokhin & Zaginaev, 2020a).

For the northern Teskey range (M. A. Daiyrov et al., 2019) find 362 glacial lakes, and for the southern Kungöy range they find 64 glacial lakes in 2015-2016. Lakes of less than 0.01 km^2 make up for about 70% of the lakes (M. A. Daiyrov et al., 2019). Similarly, ¾ of the lakes in the northern Tien Shan have areas <0.01 km^2 (Narama et al., 2018). The largest moraine-dammed lake in Kyrgyzstan is Petrov lake (Janský et al., 2009). In the Kyrgyz Ala-Too and the Kungöy Ala-Too, Zaginaev et al. (2019) report 106 outburst-hazardous lakes, which is 29% of the total number of lakes.

A monitoring system for outburst lakes, which consists of 5 stages has been developed in Kyrgyzstan.

Stage 1 - identification of outburst-prone lakes out of many mountain lakes.

Stage 2 - assessment of the degree of danger of outburst of mountain lakes.

Stage 3 - regime observations of the development of outburst lakes.

Stage 4 - assessment of possible damage from the outburst mountain lakes.

Stage 5 - development of recommendations to reduce damage from outbursts of mountain lakes.

At the 1st stage of monitoring, it is very important to identify lakes with unstable, with outburst-prone dams in order to focus work on these lakes in further research. In Kyrgyzstan, a catalog of outburst-prone lakes has been developed and compiled, which currently includes 367 lakes. New information about already existing and newly formed outburst lakes is constantly added to the catalog.

At the 2nd stage of monitoring, the lakes are divided into four categories according to the degree of their outburst hazard: Category 1 - the most dangerous. The lake is at the breakthrough stage and urgent protective and preventive engineering measures are required to be taken to prevent its possible catastrophic consequences; Category 2 - dangerous. The lake is approaching the breakthrough stage in its development, but there is no immediate threat at present; regime observations should be set up on the lake; Category 3 - less dangerous. The lake has prerequisites for a breakthrough in the future, it is currently safe and should be surveyed annually by aerial visualization; Category 4 - lakes that have already passed a breakthrough stage in their development, i.e. they have already broken through one or more times. But they still retained the possibility of accumulating significant volumes of water in lake baths and, under appropriate changes in natural conditions (earthquakes, rockfalls, landslides, mudflows), they can become outburst-hazardous. In the process of its development, the lake can several times move from one category of outburst hazard to another. Currently, out of 367 lakes included in the catalog of outburst lakes in Kyrgyzstan, 12 lakes are classified as very dangerous (category 1) and 25 lakes are dangerous (category 2). The most important criterion for the outburst hazard of lakes is their type. According to the composition of the material that makes up their dams, the lakes are divided into a number of types, of which the moraine-glacial lakes are the most outburst-prone.

At the 3rd stage of monitoring, regime observations over development of lakes of different types are carried out in order to study their peculiarities and to predict the time of possible outbursts. During the observations, the lake's feeding and its runoff is revealed, the stability of the dam is determined by identifying various types of its deformations. The formation, development and outburst hazard of mountain lakes to a greater extent depend on the nature of their runoff. Runoff can be surface, underground or mixed. During the development of the lake, the nature of its runoff changes from underground to mixed and then to surface. Lakes with underground flow are more prone to outburst than lakes with mixed flow. Lakes with surface runoff are the least prone to outbursts. The annual hydrological regime of outburst-prone lakes is divided into three periods: 1) the ice period from October till May, when the lake is under ice. The level of the lake during this period either decreases or remains constant, depending on the development of the runoff; 2) the period of lake level rise and the increase in its volume. The lake receives additional feeding from the melting of snow and ice, is freed from ice, and fills up. This period is associated with an increase in the danger of its outburst. For various types of mountain lakes, this period covers: for glacial lakes - July-August; for moraine-glacial and moraine-crossbar lakes - July-September; for moraine and dammed lakes - May-August; 3) a period of lake level decline and a decrease in its volume. For different types of mountain lakes, this period includes: July-August for glacial lakes; July-September for moraine-glacial and moraine-bedrock dammed lakes (морено-ригельных); May-August for moraine and landslide-dammed lakes; and 3) the period of lake level decline and reduction of its volume. Lakes in August-October, due to reduction of meltwater inflow, discharge water volume accumulated during the second period.

At the 4th stage of monitoring, a lot of work is carried out to assess the possible damage from the outburst of mountain lakes: 1) the mechanism of a possible outburst of the lake dam is determined and the flow rate of the outburst flow is calculated; 2) the mudflow hazard of the mountain valley through which the outburst flow will pass is assessed; 3) the area of destruction of the outburst flow is determined; 4) possible damage is assessed. At present, in Kyrgyzstan, maps of the affected areas from outburst and mudflows for most of the large mountain valleys, have been compiled. Work on compiling new maps and updating old ones continues.

At the 5th stage, recommendations are developed to reduce damage from outbursts of mountain lakes. In Kyrgyzstan, such recommendations are about the following measures: 1) development of evacuation plans for the population in the case of a lake outburst warning; 2) control over the construction of residential buildings and economic facilities in the areas affected by outburst flows; 3) eviction of residents outside such areas; 4) construction of protective structures for residential buildings and economic facilities located on the territory of the affected areas.

Table 3: Some relevant glacier lake mapping, inventorying and monitoring documents for the Kyrgyz territory.

Author/ Institution	**Region**	**Method**	**Temporal resolution**	**Spatial Resolution**	**Type**
(Bolch et al., 2011) Journal article external	N Tien Shan	Satellite imagery (Corona KH-4B, Landsat MSS, Landsat ETM+, Landsat SLCoff, Terra ASTER) manual delineation improvement	~ 1972 ~ 2000 ~ 2007	15-60 m	inventory (lake identification)
(Bormudoi et al., 2012) Journal article authors from CAIAG and Ministry of Mineral Resources of Kyrgyzstan	lake Merzbacher, Tien Shan	Satellite imagery from MODIS, ASTER, Landsat, ALOS lake surface temperature from MODIS 8 day composite, automatic meteo station, topographic map and GIS layers from CAIAG	1943 1975, 1976 1981 1990 2000 2002 Jun/Oct 2003 2006 Aug/Oct 2007 2008 2009 Mar/Oct 2010 Jul/Oct 2011	2.5-60 m	monitoring, studying
(M. Daiyrov et al., 2018) Journal paper 1st author from CAIAG	Teskey Ala-Too Kungöy Ala-Too	Seasonal lake area changes based on satellite imagery (Landsat7/ETM+ and 8/OLI). DSM from UAV and aerial photos. Ground ice changes based on DInSAR analysis using ALOS-2/PALSAR-2.	1979: photos 2016: UAV ALOS-2: 14 days repetition time 27 images from 2014-2016	SAR data: 9.1 × 5.3 m DSM error: 4.9-8.7 m	monitoring seasonal area variation
(M. A. Daiyrov et al., 2019)	Kungöy Ala-Too, Teskey Ala-Too	Landsat 8/OLI, Sentinel-2 satellite imagery; aerial photographs of the USSR	1966 1973 1977 1979	Corona / KH-3, KH-4A, KH-4B, Hexagon / KH-9 (1973, 1979)	inventory

			1991 2015 2016		suggest annual monitoring by helicopter
(Kattel et al., 2020) authors from CAIAG and Department of Applied Geology, American University of Central Asia	Kyrgyz Range	ASTER DEM, Landsat 7 (ETM+), ALOS (PRISM/AVNIR-2) and Landsat 8 OLI satellite imagery	1999 2000 2002 2007 2008 2010 2014	DEM: 30 m vertical lake area: 15 m (pan-sharpened)	inventory
(Mergili et al., 2013)	Alay range, Amu Darya catchment	Corona, ASTER, Landsat 7 SRTM V4 DEM	1968 2001 2009 (+2007, 2008, 2010)	ASTER: 15 m Corona: <5 m (pan-sharpened)	inventory
(Narama et al., 2009)	Kungöy Ala-Too & Ile Ala-Tau	ALOS satellite (PRISM & AVNIR-2), Landsat satellite (Landsat 5 TM, Landsat 7 ETM+), Corona KH-4B, Hexagon KH-9	1971 1980 1991 1999 2002 2005 2006 2007 2008	1.8 m (Corona KH-4B) 6-9 m (Hexagon KH-9) 2.5 m (PRISM) 10 m (AVNIR-2)	inventory
(Petrov et al., 2017)	Uzbekistan, included for Shakhimardan enclave in the Alai range in Kyrgyzstan	Manual lake identification based on satellite imagery: WorldView 2, IKONOS, SPOT 5 Inclusion of lakes >100m^2 and above 1500 m a.s.l.	satellite images mainly from 2010-2014	WorldView2: 0.5m SPOT 5: 2.5 m PALSAR: 10-100 m	inventory
(Petrakov et al., 2020) Journal article authors from Institute of Geology and Geophysics of Academy of Sciences Uzbekistan; Agency of Geology and Institute of Water Problems & Hydropower of Academy of Sciences Kyrgyzstan	Shakhimardan river catchment in the Alai range	Satellite imagery (Landsat 8 OLI), SRTM, WorldView-2, Ikonos, Sentinel 2B, ALOS PALSAR, An automatic interpretation based on band ratios (e.g., NDWI proposed by Huggel et al., 2002) to identify lakes was not used because the spectral reflectance of the lakes has been shown to vary and as sometimes the lake area was too small.	Sentinel: 2018	Landsat: 30 bzw. 15 m SRTM: 90 m WorldView-2: 1.8-0.5m Ikonos: 3.28-0.82 m Sentinel: 10 m ALOS: 12.5 m	inventory
(Viskhadzhieva et al., 2016) author from Institute of Water Problems & Hydropower of Academy of Sciences Kyrgyzstan	Shakhimardan catchment in the Alai range in Kyrgyzstan; Aksay catchment in the Ala-Archa catchment of the Kyrgyz range	based on methodology by Chernomorets et al. (2015)	Field work 2014-2015		inventory
(Usupaev et al., 2019) authors from Institute of Water Problems	Kyrgyzstan	classical methods of mapping and new geo-engineering methodology of integrated mapping Aerial imagery and regular survey of hazardous lakes with Mi-8 MTV	?? aerial imagery June-Sept.	??	mapping method

& Hydropower of Academy of Sciences Kyrgyzstan; and CAIAG		helicopters by the Ministry of Emergency Situations of Kyrgyzstan			
(Wang et al., 2013)	Tien Shan	Landsat satellite imagery & google earth images (SPOT-5, GeoEye, QuickBird)	1990 2000 2010	1.65-2.62m for google earth	inventory
(Xie et al., 2013)	lake Merzbacher	HJ1-A,B satellite imagery	2 days	30 m	monitoring
(V. Zaginaev, Erokhin, et al., 2019) authors from Institute of Water Problems & Hydropower of Academy of Sciences Kyrgyzstan	northern slope of Kyrgyz range	stationary observations, RS (satellite imagery, meteo stations and loggers on moraine complexes), field work (bathymetry, dam survey)	annual bathymetric measurements, daily meteo & temperature measurements	NA	monitoring
(V. Zaginaev, Falatkova, et al., 2019) Journal article some authors from the Institute of Water Problems and Hydropower of the National Academy of Science in KYR	Uchitel lake in the Aksay valley in the Kyrgyz range	satellite imagery: Sentinel-1; survey of 20 transverse and longitudinal cross section profiles in 2008 (Leica TCR 705 total station); bathymetric surveys (echo sounder); photographs from UAV	satellite: 2012, 2013, 2014, 2015, 2017, 2018; field work: 2007, 2015; bathymetry: 2013 & 2016	DEM: 10 m bathymetry: 2m steps at profiles	monitoring
(Zhang et al., 2015)	Third pole Amu Darya basin (incl. Pamir and a tiny bit of KYR)	Landsat TM/ETM+ satellite imagery; manual identification and digitisation	1990 (1987-96) 2000 (1999-02) 2010 (2009-11)	30 m; synchronization with google earth for spatial scale improvement	inventory
(Zheng et al., 2021)	Third pole	Landsat satellite imagery	1990 2015	30 m 15 m (pan-sharpened)	inventory
(Zheng et al., 2019)	upper Syr Darya catchment	Landsat 5 TM, Landsat 7 ETM+, Landsat 8 OLI NASA 30m SRTM DEM	1990 2000 2005 2010 2015	30 m 15 m (pan-sharpened)	inventory

4.2 Resolution

Glacier lake inventories cover the Kungöy Ala-Too, the Teskey Ala-Too, the Kyrgyz range, the Alay range and the upper Syr Darya catchment specifically, as well as the Tien Shan and the Third Pole more generally. Inventorying of glacial lakes is mainly based on remote sensing data obtained by satellites. Spatial resolution of satellite imagery from common satellites is around 2 to 30 m depending on the sensors used and the combination of data. Improvements in spatial scale can be achieved by pan-sharpening satellite images. Temporal resolution between annual and decadal scale for most sites. (Xie et al., 2013) state that many kinds of RS data (e.g. Aster, Spot, Landsat etc.) do not have the necessary temporal resolution to catch GLOF events like the ones produced from lake Merzbacher, that occur during 4-5 days. They rather suggest HJ1-A,B data with higher temporal (2 days) but lower spatial resolution (30 m).

4.3 Site selection

Sites for monitoring and studying were often selected (1) when they were found to have experienced GLOFs before, as in the case of Uchitel lake which is situated in the Aksay valley, and regarded as an emerging threat, since all reported GLOFs in the valley were associated with the activity in the Aksay glacier (V. Zaginaev, Falatkova, et al., 2019); (2) Based on the type of lake, dam or location to be able to study a specific process (e.g. (Narama et al., 2018), (M. Daiyrov et al., 2018). (Narama et al., 2018), for instance, specifically selected depressions for the monitoring of short-lived glacial lakes exceeding 0.01 km^2, located on debris landforms with ice, having a source of meltwater inflow, but no surface outflow channel. And (M. Daiyrov et al., 2018) selected lakes exceeding >0.0005 km^2 that are located on debris landforms at glacier fronts; (3) When there is infrastructure or settlements located downstream. The development of glaciation in the Ala Archa basin, for example, is monitored in the long term mainly due to its position in proximity of the Kyrgyz capital, Bishkek, and the popularity of the valley among tourists visiting the National Park (Falatkova et al., 2018). **Figure 5** shows the location of all lakes mapped in the most recent lake catalogue of outburst-prone lakes in Kyrgyzstan compiled by authors from the Institute of Water Problems and Hydroenergy (Erokhin & Zaginaev, 2020b).

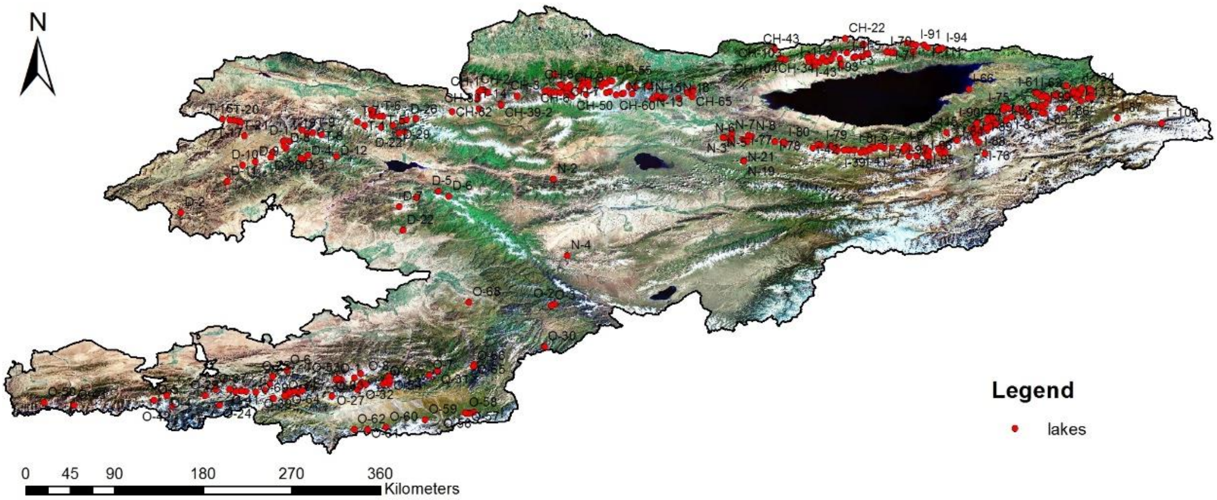

Figure 5: Map of the Kyrgyz territory with all lakes mapped in the most recent lake catalogue of outburst-prone lakes compiled by authors from the Institute of Water Problems and Hydroenergy (Erokhin & Zaginaev, 2020b).

4.4 Responsible institutions

Monitoring of high-altitude glacial lakes has been conducted by the Ministry of Emergency Situations, together with the Ministry of Natural Resources and Hydrometeorological Services (ESCAP, 2012) for the past decades. The most recent report about GLOFs was elaborated in 2015 by the Institute of Water Problems and Hydroenergy. Monitoring of emergencies related to flooding at the national level is conducted by the Department of Monitoring and Forecasting, the Office of Selvodzaschita, and the Hydrometeorology Agency (Kyrgyzhydromet), all of which are under the Ministry of Emergency Situations (ESCAP, 2012). In order to warn the population and prepare them to respond to emergencies, the Department of Monitoring and Forecasting issues forecasting and training materials. All forecasting material is recorded in the GIS system at the Centre for Crisis Management, for the coordinated operation of the State system of prevention and mitigation of emergency situations in Kyrgyzstan and along borders with other countries (ESCAP, 2012).

Most of the peer reviewed articles on lake mapping and monitoring are published by external authors and authors mainly affiliated with the Central Asian Institute of Applied Geosciences (CAIAG), the

Institute of Water Problems and Hydroenergy of the Academy of Sciences Kyrgyzstan, and to a minor degree with the Kyrgyz State Agency of Geology, the Ministry of Mineral Resources of Kyrgyzstan, and the Department of Applied Geology of the American University of Central Asia.

4.5 Methods

The detection and delimitation of glacial lakes is largely based on satellite based remote sensing, and glacial lake monitoring is based on remote sensing as well as field data. Satellite imagery is used to find depressions, to generate digital elevation models, as well as for more specific and detailed information acquisition. Digital surface models can be based on UAV images and aerial images.

While some inventories rely on automatic lake area extraction (e.g. (Xie et al., 2013)), lake delineation is often done or at least improved manually (e.g. (Bolch et al., 2011; M. Daiyrov et al., 2018; Zhang et al., 2015)). In a few sites, automatic meteorological stations provide temperature and precipitation data (e.g. lake Merzbacher) for monitoring. Loggers on moraine complexes can deliver information on lake dams in specific cases and bathymetric surveys can provide information about lake depth, lake topography, etc. (e.g. done for some lakes in the Kyrgyz range). Ground ice changes can be obtained by DInSAR analysis and are investigated in some cases in the field (M. Daiyrov et al., 2018).

4.6 Challenges

Glacial lake detection largely depends on the image quality. Presence of shadow and especially snow cover hampers the identification of high altitude lakes (Bolch et al., 2011).

Systematic monitoring of glacial lakes in Central Asia demands access to high-resolution satellite images for early prediction of a dangerous situation. Satellite images have the added advantage that they can be used to monitor hazards in and risks to neighbouring countries (ESCAP, 2012).

In all central Asian countries, there is a lack of equipment for early warning and monitoring, particularly in terms of information and communication technologies. Lack of operational satellite data and lack of specialized centres for data processing make it difficult to monitor events promptly or in real time. The use of GIS technology is underdeveloped (ESCAP, 2012).

Central Asian countries do not have a common system for rapid exchange of information during emergency situations on rivers, leading to an increased risk of catastrophic consequences. Existing systems are not sufficiently equipped or extensive enough to fully and accurately assess damage due to floods, mudslides and other hazards associated with water (ESCAP, 2012).

At the moment, the communication system in Central Asia is based principally on telephone transmission lines, which means that the warning system may be too slow for timely action. Moreover, the phone lines themselves may be damaged and disrupted as a result of the hazard. With this in mind, it is imperative to establish a system for exchanging information through communication satellites. Furthermore, language barriers between countries must be taken into account (ESCAP, 2012).

5. Hazard and Risk Assessment

GLOF and debris flow hazard and risk assessments have been undertaken as case studies for specific lakes as well as regionally or nationally for a multitude of lakes based on consistent methods. Reconstruction of glacier and lake evolution can shed light on processes in specific case studies. Process understanding is then helpful for future hazard assessment (e.g. lake Merzbacher). **Table 4** is a compilation of hazard and risk assessments for Kyrgyzstan with information on their scale, methods and similar.

Table 4: Compilation of some relevant GLOF hazard and risk assessments for Kyrgyzstan.

Author	Region and Scale	Method	Parameters	Data	Institution	Type
(Bolch et al., 2011)	N Tien Shan (Ile Ala-Too, Kungöy Ala-Too) Regional	Hazard assessment based on adaptation of (Huggel et al., 2002) and (Bolch, 2006) give weight factors to variables and parameters; probability of affectation of downstream area modified single flow model MSF,	lake characteristics, lake surroundings, characteristics of adjacent glaciers, impact on downstream areas	Satellite data (Landsat, ASTER, SRTM, DEM), MT optical or radar data, permafrost based on MAAT, (e.g. lake volume as empirical function of lake area)	Journal article (1 author from Institute of Geography of Ministry of Education and Sciences of the Republic of Kazakhstan)	hazard assessment
(Erokhin & Zaginaev, 2020b)	Kyrgyzstan National	Monitoring of changes in lake categories from 2006-2020 Development of lakes used as indicator for outburst possibility	outburst criteria according to dam stability 4 hazard categories	Satellite data (Landsat, Sentinel) Archive aerial images: Stationary monitoring; catalogue of hazardous mountain lakes	Conference proceedings authors from Institute of Water Problems & Hydropower Energy of the National Academy of Science of Kyrgyzstan	hazard assessment
(Falatkova et al., 2018)	Adygene glacier complex in the Kyrgyz Ala-Too Local	Assessment procedure based on fieldwork experience Inspired by (S. K. Allen et al., 2016; Frey et al., 2010; Huggel et al., 2004)	lake volume, lake/dam type, glacier contact, lake drainage, growth possibility	bathymetric, geodetic and geophysical survey; satellite imagery; modelling of glacier runoff evolution with GERM automated weather station situated near the Adygine glacier, pressure sensors in 3 lakes, Leica TCR 705 total station, aerial images 1962 and 1988, lake depth in 2.5 m steps using an echo-sounder mounted on a	Journal article	hazard assessment of individual lakes case study

				boat, ERT surrounding lakes and dams, GPR on the glacier		
(Janský et al., 2010)	Petrov lake in the Teskey Ala-Too, Adygine and Koltor lakes in the Kyrgyz Ala-Too Local	observation of morphology of lake basin and surrounding relief, outflow pattern and processes controlling lake development reconstruction of glacier and lake evolution hazard assessment based on (Huggel et al., 2004)	key numbers: Lake volume, moraine dam with buried ice, prob. max. discharge, abundant sediments along flow path, prob. max. flow volume, prob. max. travel distance indicators for outburst probability: dam type, ratio freeboard/dam height, ratio dam width/height, impact of waves, extreme meteorologic events	historical reports, aerial photographs, satellite imagery (SPOT: 10 m; Quickbird: 0.6 m), GPS mapping (2008) lake shorelines: geodetic total station Leica TCR 705 bathymetry: echosounder	Journal article	hazard assessment of individual lakes case study
(Petrakov et al., 2020)	Shakhimardan river catchment in the Alai range Batken region & Fergana region in KYR and UZB transboundary	3 categories of outburst potential according to qualitative and quantitative values based on methodology by (Worni et al., 2013) and used by (Perov et al., 2017)	e.g. lake area, lake type, dam type, freeboard, connectivity between lakes, drainage type, potential for lake impacts (e.g., mass-movements falling into the lake), and outburst poten-tial	satellite imagery (Landsat 8 OLI (30-15m), SRTM (90m), WorldView-2 (1.8-0.5m), Ikonos (3.28-0.82m), Sentinel 2B (10m), ALOS PALSAR (12.5m),	Journal article authors from Institute of Geology and Geophysics of the National Academy of Sciences of Uzbekistan; Kyrgyz State Agency of Geology and Institute of Water Problems & Hydropower of the National Academy of Sciences of Kyrgyzstan	hazard assessment
(Petrov et al., 2017)	Uzbekistan, but included for Shakhimardan enclave in the Alai range in Kyrgyzstan transboundary	cf. figure 7 qualitative and quantitative parameters checked by at least two independent experts for all lakes	outburst potential based on lake type, dam type, freeboard, lake connection, drainage type, possibility for lake impact	PALSAR and PALSAR-2 data on ALOS and SRTM	Journal article authors from the Institute of Geology and Geophysics in Uzbekistan	hazard assessment
(Viskhadzhieva et al., 2016)	Shakhimardan river catchment in the Alai range in Kyrgyzstan Aksay catchment in	based on methodology by (Chernomorets et al., 2015)	??		conference proceedings some authors from the Institute of Water Problems and	hazard assessment

	the Ala-Archa catchment of the Kyrgyz range local				Hydropower of the National Academy of Sciences in KYR	
(Wang et al., 2013)	Tien Shan regional	Conditions: >0.1km²; <1km distance from glacier; directly fed by melt water; increasing lake area	outburst probability based on dam type, dam geometry, dam structure, freeboard, potential for lake impacts	Landsat satellite imagery & google earth images (SPOT-5, GeoEye, QuickBird)	Journal article	hazard assessment
(Xie et al., 2013)	Lake Merzbacher in the Central Tien Shan local	outburst index based on ratio of the area change rates of floating ice and total lake → floating ice are and total lake increase consistently before the outburst. On day of drainage the area of the total lake decreases quickly whereas the floating ice will experience a slight growth in area before it plunges.	establishment of high precision area automatic extraction procedure based on characteristics of floating ice on the lake NDWI, BNIR/BR ratio between 0.9 and 1.2 is floating ice	satellite imagery from HJ1-A,B (30m, 2d) in 2009/2010, Landsat ETM+ in 2001/2002	Journal article	hazard assessment
(V. Zaginaev, 2016)	Aksay-Tone valley in the Teskey Ala-Too local	determination of boundaries of flood and mudflow damage zone based on hydrological, lithological and morphological factors	flow rate, flow density, width of valley bottom, height of outburst flow, width of outburst flow	field studies and satellite imagery: longitudinal and transversal valley profiles, slope from GPS receiver,	Journal article author from Institute of water problems and hydropower of the National Academy of Science of Kyrgyzstan	hazard map
(V. Zaginaev, Falatkova, et al., 2019)	Uchitel lake in the Aksay valley in the Kyrgyz range local	flood zones under 3 scenarios based on historical data	estimation of max. flood height,	historical reports, cross section profiles (Leica TCR 705 total station),	Journal article some authors from the Institute of Water Problems and Hydropower of the National Academy of Science in KYR	GLOF impact assessment
(Zheng et al., 2021)	Third Pole including West Tien Shan and Pamir regional	conceptual model based on (Simon Keith Allen et al., 2019) GLOF risk index as function of hazard and exposure index;	hazard key factors: lake volume, total upstream watershed area, likelihood of impact into lake, downstream slope of lake dam	Landsat satellite imagery	Journal article	risk assessment

5.1 Responsible institutions

The main Government body that monitors and forecasts flood risk, prepares for and ensures the safe passage of debris flows and floods, responds to emergencies, and is in charge of restoration of areas damaged by landslides and floods in Kyrgyzstan is the Ministry of Emergencies (ESCAP, 2012). There is a catalogue of outburst-hazardous lakes in Kyrgyzstan compiled by authors from the Institute of Water Problems and Hydroenergy that is continuously updated (Erokhin & Zaginaev, 2020b). Regional, national and local hazard assessments have been published in peer reviewed journals by international authors as well as authors affiliated with different national institutions like the Institute of Water Problems and Hydropower Energy of the National Academy of Sciences of Kyrgyzstan, or the Kyrgyz State Agency of Geology.

5.2 Methods

Hazard assessments have been based on methods developed and used in different scientific publications (e.g. (S. K. Allen et al., 2016; Simon Keith Allen et al., 2019; Bolch, 2006; Frey et al., 2010; Huggel et al., 2002, 2004; Perov et al., 2017; Worni et al., 2013)). Most assessments are index based and weigh different parameters to loosely assess the outburst probability of individual lakes. Detailed hazard assessments are often done only when the lakes fulfil certain conditions in terms of lake size (e.g. > 0.1km2), distance from glacier (e.g. <1km), direct feeding by melt water, increasing lake area etc. (Wang et al., 2013). High attention is given to non-stationary lakes that present high probability but low magnitude events.

The criteria for outburst probability and hazard categories are mostly dependent on the dam stability (Erokhin & Zaginaev, 2020b) with indicators like dam type, ratio freeboard/dam height, ratio dam width/height for example (Janský et al., 2010); as well as the possibility of lake impact and extreme meteorologic events e.g. (Petrakov et al., 2020) (Petrov et al., 2017) (Wang et al., 2013) (Zheng et al., 2021). For lake Merzbacher in the central Tien Shan (Xie et al., 2013) elaborated an index based on the ratio of the area change rates of floating ice and the total lake.

The parameters mostly used are lake characteristics (e.g. lake volume – often calculated as an empirical function of the lake area -, lake type, lake drainage, and freeboard), lake surroundings (e.g. dam type and ice presence, lake development/growth possibility, connectivity between lakes, morphology of lake basin, surrounding relief, total upstream watershed area, downstream slope of lake dam), glacier characteristics (e.g. glacier contact), characteristics of the downstream areas (e.g. sediments abundancy along flow path), and probable impact on downstream areas (e.g. max. travel distance, prob. max. discharge)

Some assessments additionally assess possible hazard magnitude and model potential impacts (in terms of area covered, debris flow height etc.) in downstream areas based on scenarios. (V. Zaginaev, 2016) developed a hazard map for the Aksay-Ton valley in the Terskey Ala-Too based on hydrological, lithological and morphological factors. The parameters used for that are mostly flow rate, flow density, width of valley bottom, height of outburst flow, width of outburst flow. Models that have been used for that purpose are single flow model (MSF) (e.g. used by (Bolch et al., 2011)), and GERM for glacier runoff evolution (e.g. used by (Falatkova et al., 2018)). Different assessment methods are presented in **figures 6** and **7** as well as in **tables 5** and **6**.

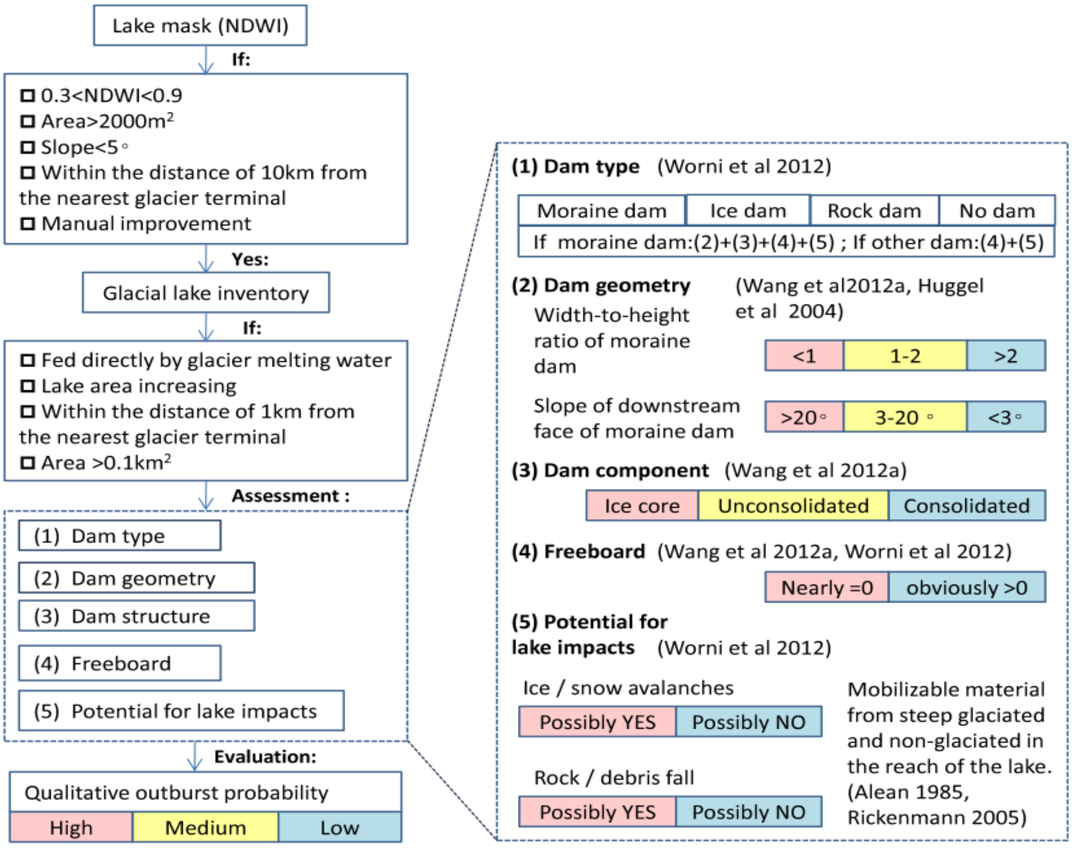

Figure 6: Flow chart illustrating glacial lake detection and lake outburst probability assessment in Tien Shan based on (Wang et al., 2013).

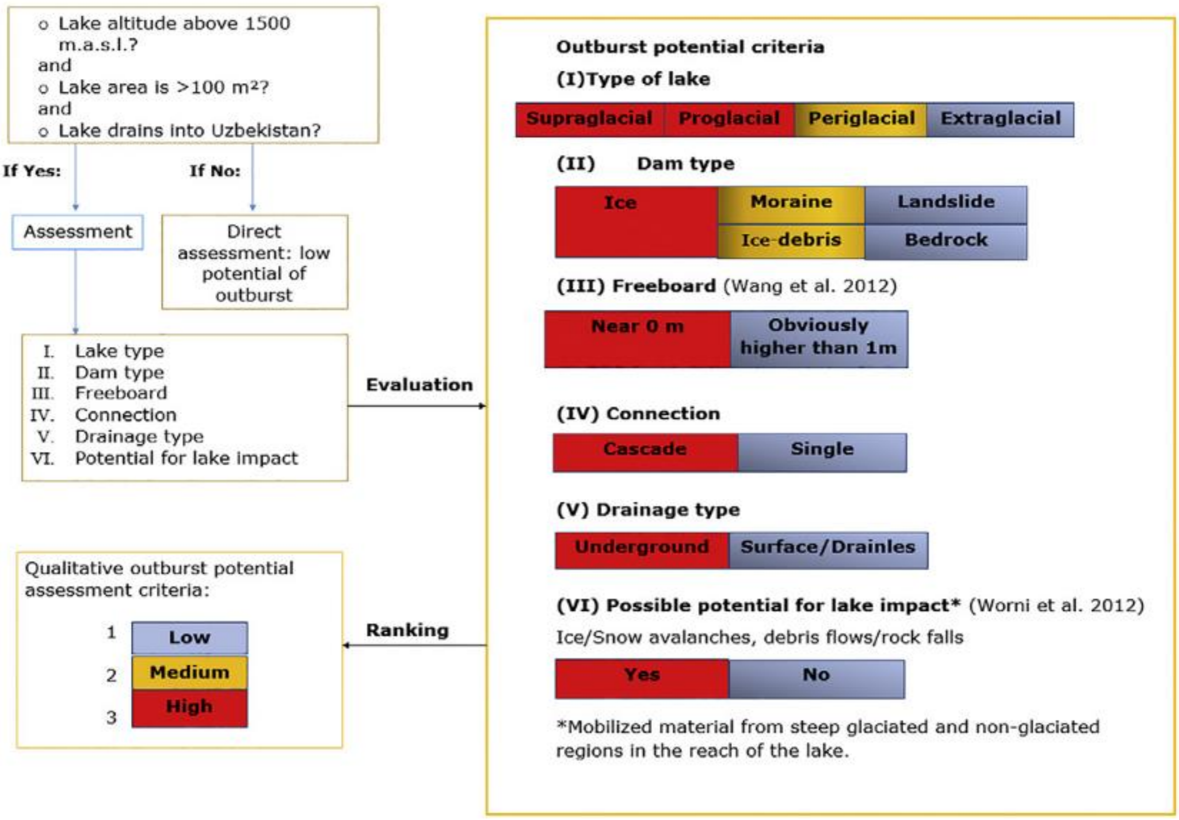

Figure 7: Flow chart illustrating glacial lake inventorying and lake outburst potential assessment in Uzbekistan from (Petrov et al., 2017).

Table 5: Criteria for categories of lake outburst susceptability of different lake types and subtypes for Kyrgyzstan and detailed description of criteria used to identify the hazard category with a focus on each genetic type of lakes (Erokhin & Zaginaev, 2020b).

Genetic class of lake	Subclass	Outburst susceptibility criteria	Hazard category
Ice-dammed	*Supraglacial* *Englacial* *Glacier-dammed*	• Rapid lake level rise in melting season • Outburst events in the past	1,2
		• Lake level is stable or gradually increasing • Outburst events in the past	3, 4
Moraine-dammed **(Ice- cored)**	*Lakes of intra-moraine depressions*	• Direct contact with glacier • Underground • Gullies and piping observed on the downstream dam face • Signs of dam subsidence along the underground channels • Amplitude of lake water level fluctuation up to several meters; • Rapid lake filling (weeks, months); potential overflow	1
		• Direct contact with glacier • Underground • Signs of dam subsidence along the underground channels • Gullies and piping observed at the dam foot slope • Amplitude of lake water level fluctuation up to several meters; • Gradual lake filling (1-3 years);	2
		• Underground/combined outflow • Signs of dam subsidence along the underground channels • Gullies and piping observed at the dam foot slope • Amplitude of lake water level fluctuation is insignificant; stable regime of water inflow and outflow • Gradual lake filling/lake level is stable;	3
		• Underground/surface (stable overflow) /combined outflow (stable) • Gradual water level decrease	4
	Thermokarst	• Underground outflow • Signs of dam subsidence along the underground channels • Ice outcropping along the lake banks • Intensive subsidence of lake basin banks and bottom; subsidence cracks • Rapid lake filling (weeks, months);	1
		• Underground outflow • Signs of dam subsidence in individual parts of lake basin banks • Gradual lake filling	2
		• Underground outflow • Insignificant lake filling	3
		• Lake level is stable or decreasing	4
Bedrock-and moraine-dammed	-//-	• Direct contact with glacier • Underground/combined outflow • Gullies and piping observed on the downstream dam face • Signs of dam subsidence along the underground channels • Amplitude of lake water level fluctuation up to several meters; • Rapid lake filling (weeks, months); potential overflow	1
		• Direct contact with glacier • Underground • Signs of dam subsidence along the underground channels • Gullies and piping observed at the dam foot slope • Amplitude of lake water level fluctuation up to several meters; • Gradual lake filling (1-3 years)	2

		• Underground/combined outflow • Signs of dam subsidence along the underground channels • Gullies and piping observed at the dam foot slope • Amplitude of lake water level fluctuation is insignificant; stable regime of water inflow and outflow • Gradual lake filling/lake level is stable	3
		• Underground/surface (in case of stable overflow)/combined outflow (stable) • Gradual water level decrease	4
Moraine-dammed **(Ice-free)**	-//-	• Underground outflow • Gullies and piping observed on the downstream dam face • Amplitude of lake water level fluctuation up to several meters; • Rapid lake filling	1
		• Underground outflow • Gullies on the downstream dam face • Gradual lake filling	2
		• Underground outflow/stable surface outflow • Gullies on the downstream dam face • Gradual lake filling • Insignificant amplitude of lake water level fluctuation • Stable regime of water inflow and outflow	3
		• Underground outflow • Gradual water level decrease	4
Landslide-dammed	*Rockslide-dammed*	• Underground outflow • Intensive erosion, gullies and piping observed on downstream dam face • Rapid lake filling	1
		• Underground outflow • Gullies on the downstream dam face • Gradual lake filling	2
		• Underground outflow/stable surface outflow • Gullies on the downstream dam face • Insignificant amplitude of lake water level fluctuation • Stable regime of water inflow and outflow	3
		• Underground outflow • Gradual water level decrease	4
	Debris-flow-dammed lake	• Absence of water outflow • Rapid water level rise/possible water overflow	1
		• Underground outflow • Gradual water level increase	2
		• Underground outflow/stable surface outflow • Insignificant amplitude of lake water level fluctuation • Stable regime of water inflow and outflow	3
		• Underground outflow • Gradual water level decrease	4
	Landslide dammed lake	• Absence of water outflow • Rapid water level rise/possible water overflow	1
		• Underground outflow • Gradual water level increase	2
		• Underground outflow/stable surface outflow • Stable regime of water inflow and outflow	3
		• Underground outflow • Gradual water level decrease	4

5.3 Data

Most hazard assessments rely on satellite data and to a minor degree on aerial images for lake detection and to extract the lake and glacier area, information on the lake surroundings, elevation, topography and similar. Historical reports and aerial images have in some cases been used to reconstruct past GLOFs, lake development etc. Field data is retrieved for specific cases of interest as it is not possible to go to the field to systematically cover all glacial lakes. Such data include bathymetric surveys using echo-sounders mounted on boats, geodetic and geophysical surveys (e.g. ERT measurements surrounding the lake and GPR on the glacier), pressure sensors in the lakes, radar data, total stations, GPS mapping and similar.

5.4 Overview of hotspots

Most of the outburst-hazardous lakes are located in the Northern Tien Shan, namely on the northern slope of the Kyrgyz ridge (V. Zaginaev, Erokhin, et al., 2019). They are distributed in different regions in the following way: Jalalabad region: 26 lakes; Issyk-Kul region: 170 lakes; Naryn region: 18 lakes; in Osh and Batken regions: 65 lakes; Talas region: 21 lakes; Chui oblast: 73 lakes (Erokhin & Zaginaev, 2020b).

Some glacial lake hotspots are mentioned here:

Kyrgyz ridge:

- Ala-Archa valley: lake at Adygene glacier, lake at Teztor glacier, lake at Uchitel glacier (V. Zaginaev, Petrakov, et al., 2019).
- Alamedin valley: rockfall dammed glacier lake (74°34′ E–74°44′ E; 42°25′ N–42°42′ N) (V. Zaginaev, Petrakov, et al., 2019).
- Aksay valley: The Aksay moraine-glacier complex is among the most dynamically developing ones in Kyrgyzstan, creating a threat to infrastructure and people associated with the road network connecting Bishkek and the national park (V. Zaginaev, Falatkova, et al., 2019).

Terskey Ala-Too:

- 5x more glacial lakes than in the Kungöy range (M. A. Daiyrov et al., 2019).
- Very high flood risk in the Ton, Jyrgalan, Okok & Tyup river basins (M. A. Daiyrov et al., 2019).

Kungöy Ala-Too:

- Lower flood risk but many villages located in the Chon Koisu and Aksu basins (M. A. Daiyrov et al., 2019).
- Highly dangerous lake No. 122 in a side valley of Chon-Kemin river (Bolch et al., 2011).

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