Synthesis report on GLOF hazard and risk in Uzbekistan

State of Knowledge

1) Background & 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 Uzbekistan

The cryosphere is a great indicator of atmospheric and environmental changes, as climate fluctuations translate in changes in essential climate variables, i.e. glaciers, permafrost and snowcover. Glaciers are also a valuable water resource, especially important for arid territories such as Uzbekistan as glaciers collect solid precipitation during winter and release it as meltwater in summer providing a reliable water supply in dry years. The Pskem river basin provides water to Tashkent, the capital of Uzbekistan, with almost 3 M inhabitants. Climate change and concomitant glacier recession has caused the development and expansion of glacial lakes in mountain areas of the world, which leads to an increasing risk of lake outbursts. Outbursts of glacial lakes represent a serious hazard especially for populated regions in the mountains all over the world (Bolch et al., 2011).

Central Asia is at the boundary between temperate and subtropical climate zones. It is characterized by a extremely continental climate and by having regional differences in seasonal and annual precipitation due to strong topographical effects. Western and north western plains of central Asia are influenced by moist air masses from the Western Atlantic region; whereas in the south and east of Central Asia mountain ranges make a barrier effect that almost completely isolate the region from moist air masses from the Indian Ocean, thus arid and cold conditions dominate in the eastern part of Tien Shan and Pamir (Barandun et al., 2020). The summer ablation and the possible combined effects of global warming and atmospheric circulation changes over the north Atlantic and north Pacific has led to a glacier mass loss of 270 ± 140 Gt and glacier area losses of 2960 ± 1030 km^2 in Tian Shan Mountains, Central Asia during 1961–2012, and this rate is almost four times the global average (Farinotti et al., 2015). The most dramatic glacial shrinkage has been observed in the outer and low-altitude ranges of the Tian Shan Mountains, which are densely populated and snow and glacial melts are particularly important for regional water resources (Sorg et al., 2012).

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) report a decrease in maximum snow cover thickness and snow cover duration at all altitudes in western and central Tien Shan but no trend in the northern Tien Shan for altitudes above 2000 m a.s.l.. (Barandun et al., 2020) report an increase in snow depth for central Tien Shan. They attribute this to an increase in winter precipitation. (Shikhov & Bykov, 2018) (IN RUSSIAN) study the applicability of global weather forecast models for calculating the cold period precipitation and snow water equivalent over the catchment area of Russian Votkinsk reservoir basin for the cold season 2016-2017.

Petrov et al. (2017) report the following with respect to permafrost: In the alpine zone of the Tien Shan Mountains, three types of permafrost zones can generally be distinguished according to altitude; these include the sub-zones of continuous, discontinuous, and sporadic or (island) permafrost (Gorbunov, 1978). Boundaries of these sub-zones have also been shown to move upward from north to south by 140 m per 1° decrease in latitude. Gorburov (1978) indicates that the lower boundary of permafrost is at approximately the same height as the mean annual air temperature (MAAT) isotherm of 0°C. This reflects the formation of debris covered glaciers or rock glaciers across the region (Gorbunov et al., 2004). In the Tien Shan, permafrost temperature has experienced a continuous warming since the 1950s leading to a thickness increase of the average active layer by 23% compared to the early 1970s (Marchenko et al., 2007). According to the results of model estimations, the lower boundary of permafrost distribution has shifted upward by about 150-200 m during the 20th century, and the area of permafrost distribution in two river catchments in the northern Tien Shan has decreased by approximately 18% (Marchenko et al., 2007)

Physically, the territory of the Republic of Uzbekistan is divided in two parts: the plains, which occupy over three-fourths of the territory (78,8%); and the mountains which occupy 21,2% (Petrov et al., 2017). Glacial area in Uzbekistan is mainly contained in the Pskem river basin, Western Tien-Shan, Tashkent region; Kashkadarya and Surkhandarya river basins, E and SE of Uzbekistan; the Shakhimardan exclave in the Hissar-Alay range in Hissar-Alay Mountains; and the the Chirchik and Akhangaran river basins in Western Tien Shan (Semakova et al., 2015; Petrov et al., 2017) (Figure 1). Kashkadarya river basin hosts the largest glaciers of Uzbekistan: Severtsova (2,3 km) and Batyrbai (2,2 km). Climate is continental and subtropical (dry, long and hot summers; cold winters) with annual temperatures ranging from -29ºC to 48ºC and precipitation in winter and spring. The Surkhandarya glazriver basin is surrounded by high mountains so the cold N and NE air masses do not reach the region so has a dry and subtropical climate (very hot, dry and sunny summers; temperate and short winters) with maximum precipitation occurring in winter and spring an falling unevenly (on mountain slopes from 500 mm up to 900 mm on southern slopes of Hissar) . It hosts the largest river in the area, Surkhandarya. The Pskem river basin is part of the Tashkent region, capital of Uzbekistan. This region can be divided in two main parts: NE part with the Chirchik river basin (with Pskem river) with higher elevations where as the SE part with the Akhangaran river basin has a flatter topography. Temperatures in the mountains range from 20°C in summer down to -30°C in winter. Precipitation in the mountains, exposed to cold air masses, is around 800-900 mm in winter and spring.

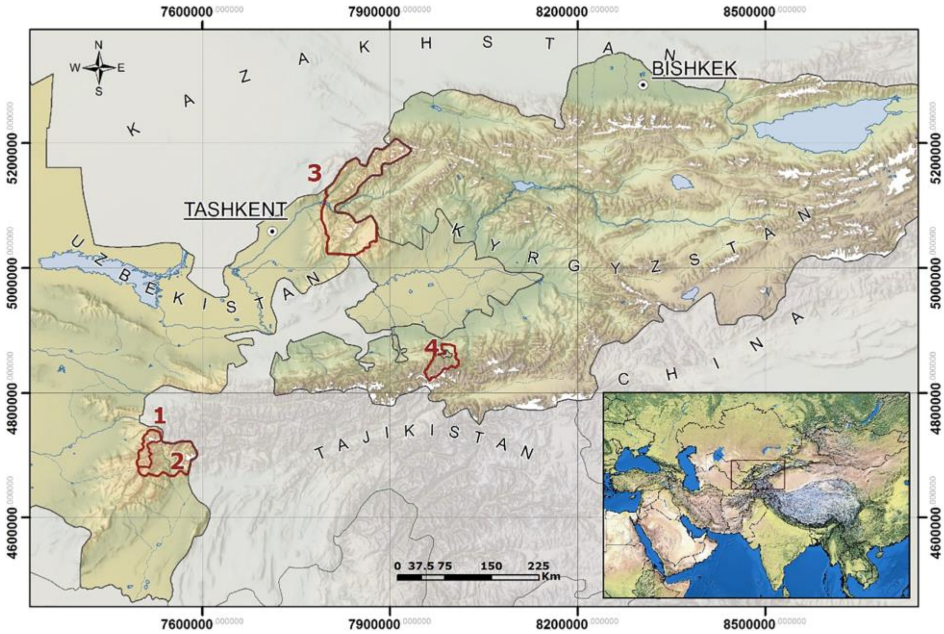

Figure 1 Mountain regions in Uzbekistan: 1) Kashkadarya; 2) Surkhandarya; 3) Tashkent; 4) Shakhimardan exclave.

Most glaciers in Uzbekistan are small in size, less than 1 km^2, lay within 2800 to 4400 m asl, and are most possibly polythermal, i.e . they contain both cold ice and temperate ice (at the melting point). Firn and ice temperatures are reliable climate indicators (Barandun et al., 2020). Past and recent on-site measurements in Central Asia show the occurrence of cold ice both in the ablation and accumulation zones (Barandun et al., 2020); however, a recent study by Kronenberg et al. (2021) found that the accumulation sites in Abramov glacier (4400 m asl, Pamir-Alay mountains) were temperate. Data on glacier thickness distribution in Uzbekistan is covered by the global dataset presented by Farinotti et al. (2019), but local studies are not known. Information on internal ice and firn structure and their change remain sparse as well; and data on glacier area is still incomplete and heterogeneous. The response of glaciers to climate change parameters in each river basin varies according mainly to precipitation, elevation and topography. Glaciological observations in Uzbekistan have been based on a limited number of ground observations. The neighboring Abramov glacier, located in the Pamir Alay, Kyrgyzstan, is a reference glacier within the Global Terrestrial Network for Glaciers. Long-term glaciological measurements exist from 1968 to 1998 and a mass-balance monitoring program was re-established in 2011 (Barandun et al., 2015). Previous detailed inventories of glaciers were carried out by Shetinnikov and partners between 1957 and 1980 including the multivolume Catalogue of Glaciers of former Soviet Union (1957-1960) and the Shetinnikov database (1978 and 1980) (Semakova et al., 2015). The majority of observation programs stopped during the early 1990s (Barandun et al., 2020). Narama et al. (2009) and Semakova et al. (2015) have assessed glacier changes in Uzbekistan using these previous detailed inventories and remote sensing data. Semakova et al. (2015) used ALOS and Landsat 8 for 2007-2010. This study identified 597 glaciers with a total area of 135.4 km^2. Glaciers in

Kashkadarya basin lost almost 50% of their volume in 50 years (1960-2010); 40% in Surhandarya basin and 27% in Pskem basin; and there has been an elevation of glacier termini in all three regions. It is also seen that most glaciers are small in size, 0.01-0.1 km^2 and 0.1-0.5 km^2, due to the disintegration of larger glaciers to small ones; and the total area of larger glaciers (>1 km^2) has decreased significantly. Due to the small size of its glaciers, the Pskem region had more glacier-area loss than neighbouring regions such as Fergana or Ala-Too ranges (Narama, et al., 2009). According to Narama et al. (2009), glacier area in the Psekm region decreased by 19% in 1970-2000 and by 5% In the period between 2000-2007, showing that recent glacier shrinkage took place at a slightly higher rate than the 1970-2000 period. In this region, glacier accumulation takes place in winter and spring. Winter-spring precipitation remained stable, thus, a general rise in summer temperatures has led to a significant glacier melt during the studied periods (Narama et al., 2009). Glacier shrinkage causes a decrease in summer runoff, which may result in water shortages for lowland inhabitants. In the Pskem region, where glaciers accumulate in the winter/spring and summers are dry, decreased summer runoff caused by glacier shrinkage may result in water shortages for residents of lowland areas, e.g. Tashkent, Chimkent, in the Pskem region. In basins with pronounced glacier cover, Shults (1965) determined the contribution of ice melt to total runoff to up to 22% over the year, and 37% during the ablation period (July–September). Based on results from high mountain river basins of Northern Tien Shan, glacier melt would contribute 18–28% to annual runoff and 40–70% to summer runoff (Aizen et al., 1995). Glazyrin et al., (n.d.) suggests that the contribution of ice water into the total river runoff in the summer can reach 20-25% for the dry year and decrease down to 10-12% in a year with intense winter precipitation.

3) Past GLOF and glacial mudflow disasters in Uzbekistan.

Hand in hand with glacier shrinkage comes the proliferation of new lakes at the retreating tongue of glaciers where topography is adequate. Glacial lakes have developed rapidly since the 1970s in the outer ranges of Tien Shan and thus the associated glacier hazards such as Glacial Lake Outburst Floods (GLOFs). Glacial Lake Outburst Floods (GLOFs) are a catastrophic release of water reservoir formed either at the side, in front, within, underneath or on the surface of a glacier. Dam structures that contain the water reservoir can be composed primarily of glacial ice, morainic debris or bedrock (GAPHAZ, 2017). The most noticeable GLOF events occurred in 1973, 1998, and 2002 in Northern Tien Shan (Tuyuksu), Hissarro Alay (Shakhimardan), and the Pamirs (Shahdara), and killed over one hundred people in total (UNEP, 2007). Over the last decades alone, Central Asian GLOFs and the resulting debris flows have killed hundreds of people and destroyed numerous houses, farmland surfaces and tourist infrastructure in Central Asia (Petrakov et al., 2020)

- **Process Types**

Mudflows are amongst the most damaging and deadly natural hazards in Uzbekistan (Mamadjanova et al., 2018)

Mamadjanova et al. (2018) writes:

"Hungr et al. (2014) suggest the term mudflow as a very rapid, sometimes extremely rapid, surging flow of saturated plastic soil in a steep channel involving significantly greater water content relative to the source material. In the river basins of Uzbekistan, mudflows generally occur during periods of intense rainfall or rapid snowmelt. The consistency of the mudflow is mainly water and mud (liquidity index> 0: 5; e.g. Hungr et al., 2001) with loose rock and other fragments, which flows down the hills

and through the mountain streams. The destructive power of a mudflow can be greatly increased moving downhill due to the accumulation of water and rocky mud. It can destroy riverbeds and banks of rivers, floodplains and even low terraces above the floodplain and other objects in its path (Chub et al., 2007)" (Mamadjanova et al., 2018).

Although lakes in Central Asia have much smaller volumes than lakes in the neighboring region of Hindukush-Karakoram-Himalaya, they have more frequently produced GLOFs and hydrogeomorphic disasters downstream of their source as they transform into destructive debris floods or debris flows down steep loose-sediment terrain with discharges up to an estimated 12,000 m^3/s and volumes of sediments of up to a few million m^3 (Petrakov et al., 2020).

According to the post-event helicopter reconnaissance by Glazyrin (1998), the 1998 catastrophic debris flow affecting the Uzbek exclave of Shakhimardan could have formed following the outburst of three glacier lakes located in stagnant ice of the Archa-Bashi Glacier, with an estimated total lake volume of 4000 m^3. The disaster started from the failure of the ice-debris dam of uppermost and largest of the three lakes, which caused its outburst into the lower lakes leading to a cascading chain reaction. Discharge of the initial outburst was estimated at 2–3 m^3/s (Glazyrin, 1998). On its way downstream, the flood wave entrained considerable amounts of sediment and larger debris through massive bank and bed erosion such that the flood was consequently transformed into a debris flow. Enough water was added to the flow by numerous tributaries with significant meltwater discharge as well as by eroded, water-saturated soils. Once reaching the settlement of Shakhimardan, the flow was estimated to have had a discharge of about 150–200 m^3/s (Petrakov et al., 2020; from Glazyrin, 1998). Prior and post-event studies done by (Petrakov et al., 2020) estimate a total area of the lake involved in the disaster at $20 \pm 1.2 \times 10^3$ m^2. Before the outburst, the water level must have increased and eventually overflown the dam. A narrow breach was then formed by the overflowing water and subsequent retrogressive erosion. After the disaster the lake was only a third of the size. According to Petrakov et al. (2020), the two lakes downstream mentioned by Glazyrin (1998) could not be found in any image prior to the disaster.

- **Known triggering and preconditioning factors**

Mudflow triggers in Uzbekistan, as considered by Mamadjanova et al. (2018), are: 1) precipitation (Huggel et al., 2012); 2) snow cover and glaciers in mountain regions (Petrov et al., 2017); 3) slope instability and temperature (Huggel et al., 2010); 4) antecedent rainfall (Glade et al., 2000; Sidle and Ochiai, 2006) and intense snowmelt (Kim et al., 2004), which may further reduce the slope stability, thus increasing potential mud and debris flow occurrences.

GLOFs occurred during the 20th century, mainly between 1960 and 1990s, originated in high-mountain lakes of Northern Tien Shan coinciding with phases of glacier stagnation or slight glacier advances (Zaginaev et al., 2016, 2019; Petrakov et al., 2020).

According to the post-event helicopter reconnaissance by Glazyrin (1998), the 1998 catastrophic debris flow "Shakhimardan event" took place only days after a massive heatwave over the Alai Range which would have led to a rapid melting of ice and snow and to a rapid filling of the lakes with abundant meltwater (Glazyrin, 1998).

Mamadjanova et al. (2018) analyzed historical data of mudflow occurrences in Uzbekistan provided by the Centre of Hydrometeorological Service of the Republic of Uzbekistan (Uzhydromet) for more than 140 years. During this period a total of about 3000 mudflow events were observed (about 21 events per year on average). They found that the majority of mudflows occurred during the advection of westerly airflow when moist air from central and southern Europe reaches Uzbekistan. Their results show that westerly airflow Circulation Weather Type (CWT) initiates relatively more mudflow events comparing to other CWTs, and that westerly, south-westerly and cyclonic weather types require less antecedent rainfall to trigger mudflow occurrences in Uzbekistan (Mamadjanova et al., 2018).

- **Impacts on society in terms of losses and fatalities.**

Data from the Centre of Hydrometeorological Service of the Republic of Uzbekistan (Uzhydromet) suggest that mudflows were responsible for over 38 deaths and damaged approximately 3000 households and 5000 Ha of agricultural crops over the decade 2005–2014 in Uzbekistan (Mamadjanova et al., 2018) (Table 1).

Table 1 Mudflow disasters causing fatalities and other relative damages over the period of 2005–2014 in Uzbekistan (data source: Uzhydromet; taken from Mamadjanova et al. 2018)

Year	Number of deaths	Number of household damages	Livestock head counts	Highways (km)	Local bridges (count)	Hydrologic bridges or tools (count)	Schools (count)	Other (count)	Cotton fields (ha)	Wheat fields (ha)	Gardens (ha)	Other (ha)
2005		860			1			2	200	69		
2006	7	175						2	152	165	118	22
2007		8	1	6	15	7		3		2		6
2008	7	413	1	0.3	5			49	747	261		123
2009	8	498	80		14	5	2		966	834	56	18
2010	8	41			6		2	7		5		3
2011	2	94	50	0.5		1		52	483.5	318.6	0.12	10.1
2012	5	773	3	2.7	25	6	1	55				
2013	1	31		0.012	2	6		3				200
2014								4				
total	38	2893	135	10	68	25	5	177	2548	1655	174	382

The deadliest GLOF and debris flow disaster in Central Asia for the past 100 occurred on July 7th 1998 on the territories of Kyrgyzstan (Batken Region) and Uzbekistan (Ferghana Region) (Petrakov et al., 2020). In terms of losses and fatalities, the disaster mostly affected the settlement of Shakhimardan, the Uzbek exclave in Kyrgystan. More than 100 people were killed, an estimated 500–600 persons were reported missing (ICRC, 1998), some 14,000 people evacuated, 500 lost their houses, mostly in Uzbekistan, and the homes of at least 5000 Kyrgyz citizen were severely damaged (Reuters, 1998). The transboundary nature of this disaster prevented timely alerts and resulted in increased tensions between the two nations (Petrakov et al., 2020). As a result of the political tensions, post-event activities were restricted to a helicopter reconnaissance (Glazyrin, 1998). No scientific assessment of the event nor an inspection of the headwaters of the Aksu catchment was possible at the time of the event due to tensions between the two countries exacerbated further by the disaster.

Akhmedov and Salyamova, (2018) (IN RUSSIAN) describe mudflows in Uzbekistan and their impacts on society in terms of damage, losses and fatalities. They also address the transboundary characteristics of mudflow events in Uzbekistan.

- **Where have the events occurred**

The most noticeable, recent GLOF events occurred in 1973, 1998, and 2002 when GLOFs in Northern Tien Shan (Tuyuksu, Kazakhstan), Hissarro Alay (Shakhimardan, Uzbekistan and Kyrgyzstan), and the Pamirs (Shahdara, Tajikistan) killed over one hundred people in total (UNEP, 2007) (Table 2).

The deadliest GLOF and debris flow disaster in Central Asia occurred on 7 July 1998 on the territories of Kyrgyzstan (Batken Region) and Uzbekistan (Ferghana Region) in the Shakhimardan river catchment, Hissar-Alay, when the outburst of a small lake formed a chain of GLOFs from Archa-Bashy glacier in Kyrgyzstan and triggered a debris flow, killing over 100 people in the Shakhimardan enclave of Uzbekistan (Chernomorets, 2015). The transboundary nature of this disaster prevented timely alerts and resulted in increased tensions between the two nations. 100 people were killed by the disaster that has often been referred to as the "Shakhimardan event" after the settlement that was the most affected.

Table 2 Table taken from Petrakov, t al., 2020. Overview of main catastrophic GLOFs in Central Asia. "Note that data on victims might not be robust because they were kept secret during the Soviet period. MDFD=maximum debris flow discharge; DFV = debris flow volume.

Date	Location	River (basin), mountain range	Victims	Other information	Sources
July 7, 1963	Lake near the Jarsay Glacier and Issyk Lake, Esik town (Kazakhstan)	Issyk River (Ili River basin), Ile Alatau (North Tien Shan)	52	Esik town; 2 streets destroyed. MDFD: 7–12,000 m^3/s DFV: 5.8 million m^3	Yafyazova, 2007
July 15, 1973	Lake No. 2 near the Central Tuyuksu Glacier, Almaty (Kazakhstan)	Kishi Almaty River (Ili River basin), Ile Alatau (North Tien Shan)	70	MDFD: 10,000 m^3/s DFV: 3.8 million m^3	Yafyazova, 2007
August 3–4, 1977	Lake No. 13 near the Sovetov Glacier, Almaty (Kazakhstan)	Kumbelsu River (Ili River basin), Ile Alatau (Northern Tien Shan)	unknown	MDFD: 10,000 m^3/s DFV: 2.4–3.2 million m^3	Yafyazova, 2007
July 8, 1998	Lake near the Archa-Bashi Glacier, Shakhimardan exclave (Uzbekistan) and Kadamjay District (Kyrgyzstan)	Shakhimardan River (Syr Darya River basin), Alai Range	100	Property damage 700 million US$	*Mitigating the Adverse Financial Effects of Natu Hazards on the Economies of Central Asia: A Stu Catastrophe Risk Financing Options*, 2009
August 7, 2002	Lake near the Dasht Glacier, Roshtkala District (Tajikistan)	Shakhdara River (Amu Darya River basin), Pamir	23 (24) people	75 houses destroyed; 501 people without shelter. DFV: 1.0–1.5 million m^3	Mergili et al., 2011; IFRC, 2003; UNEP, 2007
July 24, 2008	Western Zyndan Lake near the Western Zyndan Glacier, Tong District (Kyrgyzstan)	Zyndan River (Tong River Basin), Teskey Ala-Too Range (Central Tien Shan)	3	Discharged water volume: 0.437 million m^3	Narama et al., 2010

4) Lake mapping and monitoring

Climate change and glacier recession has caused the development and expansion of glacial lakes in mountain areas of the world leading to an increasing risk of lake outbursts which represent a serious hazard especially for populated regions in the mountains all over the world (Bolch et al., 2011).

Detailed studies of mountain environments in Central Asia started at the beginning of the 20th century (Merzbacher, 1905; Korjenevskiy, 1922) and continued with the State Cadaster of Hydrology during the Soviet Union period (Nikitin and Gorelkin, 1977). After World War II, when records and studies of mountain environments resumed, a considerable number of GLOFs were reported in Northern Tien Shan (Kubrushko and Staviskiy, 1978; Kubrushko and Shatrabin, 1982; Petrov et al., 2017).

The majority of the Uzbekistan lakes belong to three general genetic types: ice-dammed, moraine-dammed and landslide-dammed lakes (Nikitin 1987 ; Glazirin 2013).

In general terms, a first short-term trend can be observed with an increase in the number of glacial lakes and of lake volumes caused by increased glacial meltwater which has a certain alleviating effect on regional water shortages. However, as global warming causes mountain glaciers to retreat or disappear, the first expansion due to increased glacial meltwater will be followed by a shrinkage as the supply glaciers recede (Zheng et al., 2019).

SANIGMI compiled a catalogue of lakes of the mountains surrounding Uzbekistan in 1999-2000 to assess the number and some characteristics as an inventory (length and width) but don´t provide other important information such as size, regime or dam type (Glazirin et al., n.d.).

- **Temporal and spatial resolution of the mapping and monitoring.**

Petrov et al. (2017) provide an inventory of mountain lakes of Uzbekistan for the years 2010-2014 using satellite images from WorldView-2, SPOT5, and IKONOS with a spatial resolution from 0.5 to 2.5 m. This satellite data was complemented with field-work and data from field studies of the last 50 years. Petrov and colleagues used topographic data from PALSAR, ALOS and SRTM. Lakes were considered if they were located at altitudes above 1500 m asl and if they had areas >100 m^2.

Previous inventories were available in Soviet archives and primarily included localized in-situ data and case-study investigations of mountain lakes in the region, e.g. for IIkhnach, Shaurkul, or Ozerniy lakes (Yakovlev and Batirov, 2003; Glazirin and Glazirina, 2012; Glazirin, 2013; Semakova et al., 2015), or regionally focused analyses (Glazyrin et al., 2013), which were mostly limited to the Tashkent region (Petrov et al., 2017). Between 1966 and 1975 over 300 mountain lakes were monitored in-situ in the Central Asia region (Petrov et al., 2017). Bathymetric surveys as well as morphological and morphometric studies were realized (Staviskiy and Jukov, 1968; Reyzvih et al., 1971; Nikitin and Gorelkin, 1979). Some of the first inventories of mountain lakes of Central Asia were published in 1967 and updated in 1980 (Nikitin, 1987).

Previous inventories were based on automatic identification of lakes in satellite data with a spatial resolution of images typically more than 30 m, thus leading to an error exceeding 40% for lakes with an area of less than 2000 m^2 (Semakova et al., 2015). However, small lakes (<2000 m^2) can cause small outburst volumes or modest peak-discharge values that may result in dangerous debris flows in steep gradient channels (Haeberli, 1983). Small lakes can also be found in vertical sequences or cascades where several lakes either have a hydraulic connection or are located in proximity at different elevations. The outburst of one lake could trigger the outburst of multiple lakes creating a debris flow whose volume significantly exceeds the initial outburst (Evans and Delaney 2015). Thus, Semakova and colleagues found it necessary to take into account small lakes with areas <2000 m^2.

Semakova et al., (2015) used multi-temporal optical remote sensing to identify potentially dangerous naturally dammed lakes in mountain regions of W Tien Shan and Hissar-Alay (E and SE Uzbekistan). They used ALOS imagery from 2006-2011 period and Landsat 8 data for 2013 as well as topographic maps, google earth images and previous inventories together with field data from in-situ observations. Multi-temporal images allow revealing the dynamics for several lakes in the area: number and area of mountain lakes vary considerably from year to year and within one summer season.

Zheng et al. (2019) use Landsat-5 (TM), Landsat-7 (ETM+) and Landsat-8 (OLI) to monitor the changes and dynamics in high mountain lakes at the headwaters of the Syr Darya River and covered the years 1990s, 2000, 2005, 2010 and 2015 (±1 year). They improved the spatial resolution from the initial 30m to 15m of Landsat ETM+ and OLI scenes by fusing with high-resolution panchromatic band based on a nearest neighbor diffusion pan-sharpening algorithm. For topography they used the NASA 30m SRTM DEM. Uncertainties from data primarily come from the spatial resolution of the imagery. The total uncertainty of the lake area measurements using Landsat datasets for Zheng et al. is 37.85 km^2, i.e. 2.33%.

- **Methods used**

Petrov et al. (2017) provide an inventory of mountain lakes in Uzbekistan and assess their outburst potential using high-resolution satellite imagery (0.5 to 2.5 m) from WorldView2 IKONOS, SPOT5 and other available free web portals mainly from 2010 to 2014 during the warmer months. Lakes were manually identified in the high-resolution satellite imagery at altitudes above 1500 m a.s.l. and with an area over 100m^2. They classified the lakes with respect to their position relative to the glaciers (supraglacial, proglacial, periglacial and extraglacial); and also classified the types of dams (ice, ice-debris, moraine, landslide and bedrock). They defined two types of connections between the lakes: closed type drainage with high hydrostatic pressure from water on the sides of the dam; and open type of drainage with rivers that flow outside of dam which can also erode the riverbanks and increase flow capacity. They also consider two configurations between lakes: single lakes and cascades of two or more lakes. They identified 242 lakes, most of them located in the Tashkent region. Results were verified in-situ in several mountain lakes, apart from Surkhandarya and Shakhimardan regions which have restrictions for such studies to be conducted in the field, therefore validation is lacking. The biggest lake has a water surface of almost 395 m^2 and the smallest of almost 118 m^2. Petrov et al. (2017) found lakes to be in three elevation intervals: 1700-1900 m a.s.l., extraglacial, landslide dammed, and have a relatively large areas; 2300-2500 m a.s.l., being extraglacial and periglacial lakes; and 3500-3700 m a.s.l. which are mainly periglacial or proglacial and have relatively small areas.

Semakova et al. (2015) used multi-temporal satellite images to identify potentially dangerous naturally dammed lakes in Pskem, Kashkadarya and Surhandarya basins. They used ALOS imagery from 2006-2011 period and Landsat 8 data for 2013 as well as topographic maps, google earth images and previous inventories. They also included data from previous field studies from in-situ observations of Pskem river basin for 2011-2012, Barkrak and Tekesh glaciers and moraine lake; and Kashkadarya river basin in 2013, 7 landslide lakes near Batirbay Glacier (Tomashevskaya & Koldaev, 2014). They manually digitalized the outlines of glaciers and lakes mainly using images from 2007 (but also from 2010 for the northern study area). They results identify: 110 lakes (1.812 km^2) in the Pskem River basin (including 45% of small-sized ponds with areas <0.002 km2); 17 lakes (0.258 km^2) in the Kashkadarya River basin; and 50 lakes (0.445 km^2) in the Surhandarya River basin. Of all lakes, more than two-thirds of the lakes in the basins are glacial and the number and area of high-mountain lakes vary considerably from year to year and within one summer season.

Glazyrin et al. (2013) did helicopter observations in the years 1999-2000 and show that lakes vary considerably in number and size from year to year (Semakova et al., 2015).

Differences exist between studies mainly lying on the methods used to identify lakes. e.g. in the Oygain basin: Glazyrin et al. (2013), based on helicopter reconnaissance, described 30 lakes, whereas Petrov et al. (2017) find a total of 61 lakes. Differences have also been found with data provided by Semakova et al. (2015), who used semi-automatic identification of lakes with Aster and Landsat together with a set of field data, restricting the minimum area of water surface to 500m^2 and with high uncertainty for lakes <2000m^2. As a result of these differences, Petrov et al. (2017) call for a clearer definition and the approval of common protocols for future studies aiming at lake identification and classification.

Zheng et al. (2019) delimited lake extents using a consistent manual digitization by a single operator with the standard Landsat false colour composite images (NIR, Red, Green bands as RGB). The minimum mapping unit was set to 2000 m^2 (aprox. 3 pixels for Landsat TM and 9 pixels for pan-sharpened ETM+ and OLI images). Lakes were classified in four types. A first differentiation was nonglacial / glacial. Lakes were considered glacial lakes if they were within the 10 km glacier buffer zone. Glacial lakes were classified as: proglacial, unconnected-fed, unconnected-nonfed. To study the dynamics of high mountain lakes, Zheng and colleagues used a unique code in different periods using ArcMap 10.2 platform. Their results show a total of 959 lakes covering a total area of 328.39 ± 5.51 km^2 for 2015. Glacial lakes account for 58% of the total quantity and only 4% of the total area. Proglacial lakes range from 3365 m to 4235m a.s.l.; unconnected-fed were found to be between 3368 and 4133 m a.s.l.; and unconnected-nonfed are between 3229 and 3926m a.s.l. Lake Song Kol, the largest lake in this basin, contributes 85% alone of the total lake area. The area the remaining lakes is relatively small. The Naryn River basin contains 91% of the total number and 98% of the total area, whereas the Kara Darya River basin has a small remaining portion of lakes. A clear growth trend in both total number and total area is observed. From 1990s to 2015, the total number of lakes increased by 205, glacial lakes (mainly proglacial) increased by 141, and the total area expanded by 6.64 km2. The increased relative area change rate in proglacial lakes indicates that the glacial retreat at the headwaters of the Syr Darya River intensified during the 1990s–2015. During the studied period, Zheng and colleagues found 91 new lakes with areas between 0.002 and 0.6 km^2 from which 65% were new glacial lakes (36% of them proglacial) and accounted for 61% of the total area. They also found 54 extinct lakes from which 47 were glacial lakes (85% of total extinct lake area, mainly proglacial and glacial-fed). Zheng et al. (2019) attribute the disappearance of lakes to three main factors: 1) human activities; 2) possible GLOFs; 3) shortage of recharge water sources such as insufficient water supply from low precipitation periods or insufficient glacial melt-water due to glacier retreat.

Petrakov et al. (2020) used the same criteria as Petrov et al. (2017) for: 1) the identification of lake types but used the buffer of 2 km to determine the extraglacial/ periglacial limit; 2) the classification of dam types. They also assessed the potential for "cascading events", drainage type, potential lake impacts (for lakes >5000m^2). Petrakov and colleagues also assessed the potential formation of new lakes in Shakhimardan catchment with both automated and manual approaches.

5) Hazard and Risk Assessment

- **Scale of the assessments**

Petrakov et al. (2020) provide an in-depth study of the 1998 catastrophic Shakhimardan GLOF event. They focus their studies on the Shakhimardan catchment.

Mamadjanova et al. (2018) do a national study looking at historical data from 1870-2014 where they look at mudflows and their relationship with precipitation and weather types using multiple and coherent systematic approaches for Uzbekistan. They found that more than 90% of all recorded mudflows were associated with extreme precipitation events, hail and sleet; and approximately 80% of all recorded mudflow episodes with different origins occurred during the period of April–June. Being the Fergana valley the most affected by mudflows.

Kulmatov et al. (2021) do a GIS analysis of the dynamics of changes in the water level, surface area, and water volume for 1993– 2017 of the Aydar-Arnasay Lake System (AALS), middle of the Syrdarya River, S of the Chardara Reservoir, Jizakh and Navoi provinces of the Republic of Uzbekistan.

Akhmedov and Salyamova (2018) (IN RUSSIAN) address the transboundary characteristics of mudflow events in Uzbekistan.

Zaginaev et al. (2019) study a multi-century dataset of regional GLOF and debris flows reconstruction for the Tien Shan based on tree-ring analyses from six different torrential fans, and provide insights on regional processes activity.

- **Assessment methods used**

Petrov et al. (2017) developed a hazard assessment for potential outburst of 242 lakes in Uzbekistan. Their assessment was based on 16 key parameters considered the most relevant for Central Asian, from which the main parameters were defined both quantitatively and qualitatively. Based on a total of 7 main variables (i.e., lake type, dam type, freeboard, connection, drainage type, possibility for lake impact) and 3 sub-variables (dam width, width-to-height ratio, dam length) for dam geometry, Petrov and colleagues realized an outburst potential assessment for all lakes. The final classification was summarized in 3 categories of outburst potential (1=low, 2=medium, and 3=high) (Figure 2). 15% of lakes are considered to be prone to outbursts, 75% have an average level of outburst potential, and 10% a low outburst potential. Petrov and colleagues accounted 97 lakes with high outburst potential which were found at the highest altitudes of the catchments, on average at about 3400 m, in the periglacial zone and often part of a cascade of lakes with ice or ice-debris dams, and mainly in the Tashkent region.

Petrakov et al. (2020) reviewed the lake inventory and lake outburst potential for the Shakhimardan River catchment previously done by Petrov et al. (2017), using the same parameters and approach to render assessments comparable over time. Petrakov and colleagues provide an in depth study of the lake situation prior and post-event for the July 1998 Shakhimardan GLOF using aerial photographs, satellite images and their reviewed lake inventory and parametrization.

Petrakov et al. (2020) assessed the stability of existing lakes and the potential for new lakes to form in depressions (or sinks) in the periglacial domain, where lakes occur today. The assessment identified 32 lakes in the Shakhimardan catchment located at elevations mainly between 4000–4200 m asl (with only one lake above 4200 m asl). They estimated that all but four lakes could possibly be impacted by potential mass movements and gathered that the freeboard in most cases is <1 m. They assessed the outburst potential of 7 lakes with areas >5000 m^2 and found that 4 of them have high outburst potential.

Mamadjanova et al. (2018) set the basis from which to study the influence of precipitation patterns on mudflow occurrences under climate change scenarios across Uzbekistan and Central Asia. (Mamadjanova et al., 2018) 1st examine historical mudflow data for over 140 years (1870-2014); 2) they empirically develop local synoptic weather types (SWTs) manually assigned to the observed mudflow occurrences; 3) they use the objective CWT approach to identify the atmospheric circulation and its relationship with the observed precipitation and their joint impact on mudflow occurrences; 4) they evaluate the precipitation threshold triggering mudflow events in Uzbekistan using an empirical–statistical antecedent daily rainfall model (ADRM) (Glade et al., 2000); finally, 5) the objective CWT method and the statistical ADRM are combined to estimate weather types which are most likely to trigger mudflow occurrences in the study area.

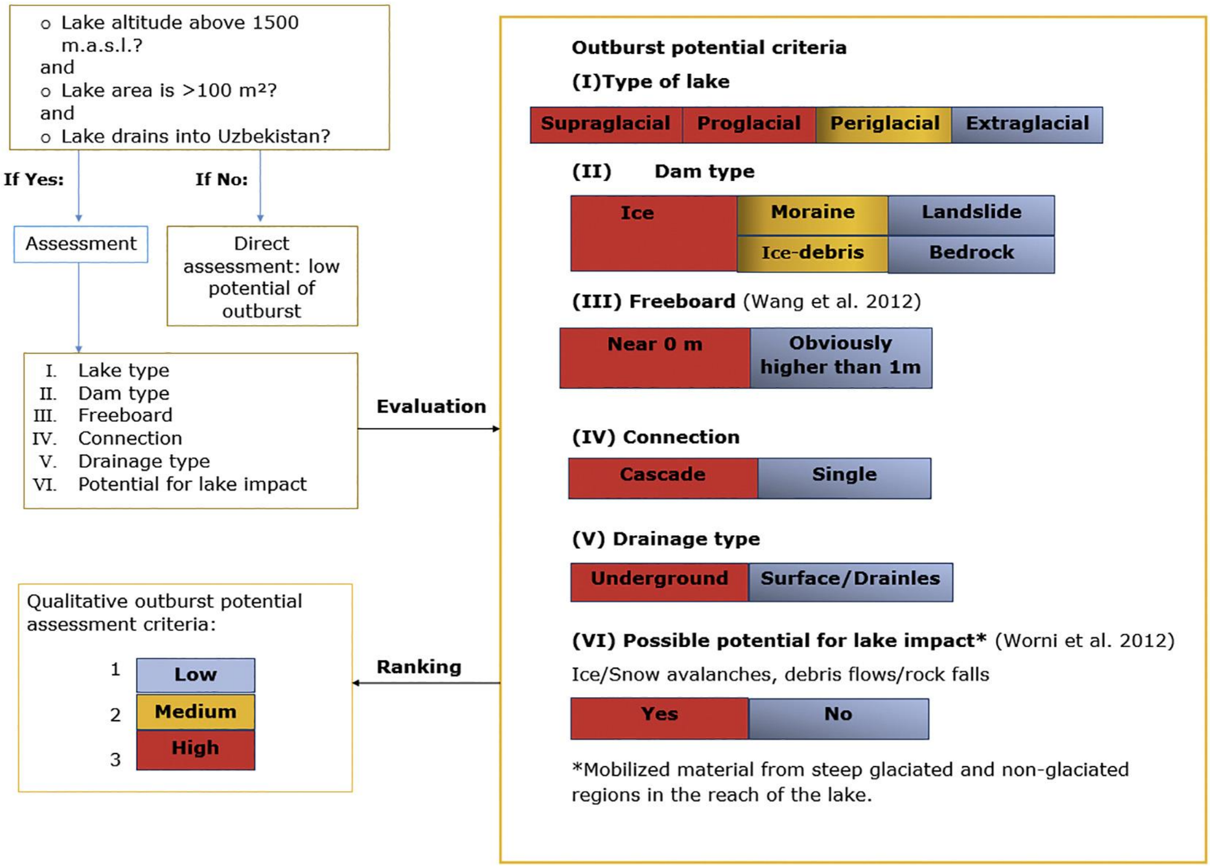

Figure 2 Flow chart from Petrov et al. (2017), illustrating the framework used for the creation of the inventory of mountain lakes of Uzbekistan and for the classification of lake outburst potential.

- **Data used**

Petrov et al. (2017) do an evaluation and classification of lake outburst potential by high-resolution remote sensing. Remote sensing results of lake area and classification of outburst potential are validated and complemented with a large set of field-measurements. For Petrov and colleagues, the main limitation of the remote sensing approach was the characterization of lake drainage type and dam type as well as the geometry. They provide a first-order approach to identify critical lakes where further analysis and monitoring will be needed.

- **Overview of hazard and risk hotspots**

15% of which are considered to be prone to outbursts, 75% have an average level of outburst potential and 10% a low outburst potential.

Mamadjanova et al. (2018) analysed historical data from the Centre of Hydrometeorological Service of the Republic of Uzbekistan (Uzhydromet) and found that the areas with a high passage of mudflow occurrences in Uzbekistan can be divided into five regions: Fergana Valley, the Zerafshan basin included in Zerafshan Valley, and the Surkhandarya, Kashkadarya and Chirchik– Akhangaran river basins.

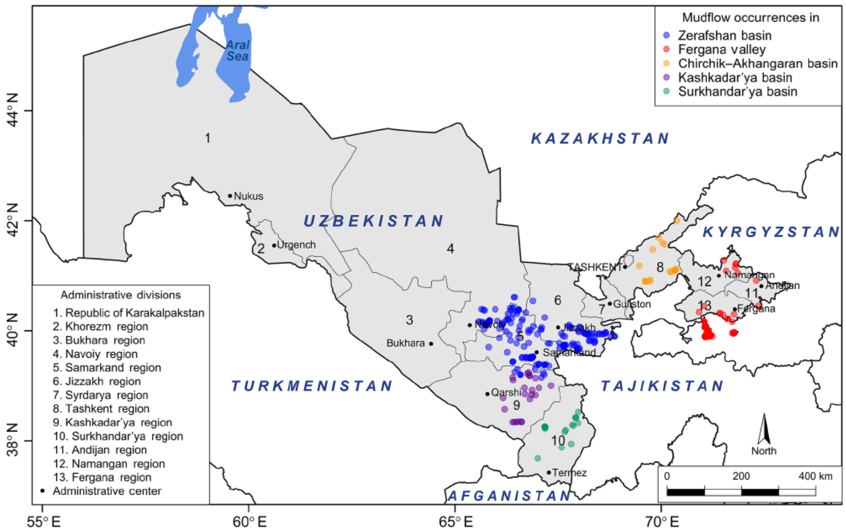

Figure 3 Mudflow occurrences for the years 2005–2014 in areas with a high probability of mudflow passage in Uzbekistan. Taken from Mamajanova et al. (2018).

- **Risk management and response**

Inventorying mountain lakes of Uzbekistan and to assess their outburst potential is a first step to wider study the region and is of great help for land-use organization and emergency planning in Uzbekistan (Petrov et al., 2017). A first-order approach to identify critical lakes with high and medium outburst potential is helpful to identify hotspots for analysis and monitoring. Mudflows are amongst the most damaging and deadly natural hazards in Uzbekistan. Data from the Centre of Hydrometeorological Service of the Republic of Uzbekistan (Uzhydromet) suggest that mudflows were responsible for over 38 deaths and damaged approximately 3000 households and 5000 ha of agricultural crops over the decade (2005–2014) in Uzbekistan (Mamadjanova et al., 2018).

Petrov et al. (2017) have assessed the outburst potential of their lake inventory on the basis of other remotely-sensed inventories and have identified key parameters considered most relevant for Central Asia. Based on a total of 7 main variables (i.e., lake type, dam type, freeboard, connection, drainage type, possibility for lake impact) and 3 sub-variables (dam width, width-to-height ratio, dam length) for dam geometry, an outburst potential assessment has been realized for all lakes. The final classification was summarized in 3 categories of outburst potential (1=low, 2=medium, and 3=high) (Figure 2). For each lake, the main parameters for the outburst potential assessment were defined by two approaches, i.e. by measuring values (quantitatively) and by visually identifying (qualitatively) different variables in the image. The largest numbers of lakes with a high outburst potential is situated in the periglacial zone, and are often part of a cascade, with ice or ice-debris dams, and situated on or next to the glacier.

BIBLIOGRAPHY

Aizen, V.B., Aizen, E.M., Melack, J.M., 1995. Climate, snow cover and runoff in the Tien Shan. Water Resources Bulletin 31 (6), 1–17.

Akhmedov and Salyamova, Bulletin of the University of Civil Protection of the Ministry of Emergencies of Belarus, Vol. 2, No. 2, 2018

Barandun, M., Fiddes, J., Scherler, M., Mathys, T., Saks, T., Petrakov, D., & Hoelzle, M. (2020). The state and future of the cryosphere in Central Asia. *Water Security*, *11*, 100072. https://doi.org/10.1016/j.wasec.2020.100072

Barandun, M., Huss, M., Sold, L., Farinotti, D., Azisov, E., Salzmann, N., Usubaliev, R., Merkushkin, A., & Hoelzle, M. (2015). *Re-analysis of seasonal mass balance at Abramov glacier 1968 – 2014*. *61*(230), 1103–1117. https://doi.org/10.3189/2015JoG14J239

Bolch, T., Peters, J., Yegorov, A., Pradhan, B., Buchroithner, M., & Blagoveshchensky, V. (2011). Identification of potentially dangerous glacial lakes in the northern Tien Shan. *Natural Hazards*, *59*(3), 1691–1714. https://doi.org/10.1007/s11069-011-9860-2

Chub, V. Y., Trofimov, G. N., and Merkushkin, A. S.: Mudflows in Uzbekistan, Uzhydromet, Tashkent, 109 pp., 2007 (in Russian).

ESCAP. (2012). *Compendium on Water-related Hazards and Extreme Weather Events in Central Asia and Neighbouring Countries*.

Evans, S.G., & Delaney, K.B. (2015). Catastrophic Mass Flows in the Mountain Glacial Environment. Snow and Ice-Related Hazards, Risks, and Disasters. 563 - 606. Elsevier

Farinotti, D., Longuevergne, L., Moholdt, G., Duethmann, D., Mölg, T., Bolch, T., Vorogushyn, S., & Güntner, A. (2015). Substantial glacier mass loss in the Tien Shan over the past 50 years. *Nature Geoscience*, *8*(9), 716–722. https://doi.org/10.1038/ngeo2513

Farinotti, D., Huss, M., Fürst, J. J., Landmann, J., Machguth, H., Maussion, F., & Pandit, A. (2019). A consensus estimate for the ice thickness distribution of all glaciers on Earth. Nature Geoscience, 12(3), 168–173. https://doi.org/10.1038/s41561-019-0300-3

GAPHAZ. (2017). *Assessment of Glacier and Permafrost Hazards in Mountain Regions: Technical Guidance Document*.

Glade, T., Crozier, M., and Smith, P.: Applying Probability Determination to Refine Landslide-triggering Rainfall Thresholds Using an Empirical "Antecedent Daily Rainfall Model", Pure Appl. Geophys., 157, 1059–1079, https://doi.org/10.1007/s000240050017, 2000.

Glazyrin, G.E., 1998. Brief Information on the Flood (Debris Flow) Occurred in the Shakhimardan River Catchment on July 8, 1998 (Unpublished Results. (In Russian).

Glazirin, G., 2013. Key locations of naturally dammed lakes in Uzbekistan. Shak. Verl. 3–20.

Glazirin, G. E., Petrov, M. A., & Sabitov, T. Y. (n.d.). Influence of the modern climatic setting in the mountains of Central Asia on the state of glaciation, glacier runoff and glacial lake outbursts. *Manuscript*.

Glazirin, G., Glazirina, M., 2012. Catalogue of Pamir and Hassaro-Alay glaciation for 1980 (database of A.S.Schetinnikov). Exlib. LLP.

Glazirin, G., Shamsutdinov, V., Starygin, G., Khan, V., 2013. Inventory of glacial lakes in the territory surrounding Uzbekistan. Shak. Verl. 54–74.

Gorbunov, A.P., 1978. Permafrost Investigations in High-Mountain Regions. Arct. Alp. Res. 10, 283–294. doi:10.2307/1550761

Gorbunov, A.P., Marchenko, S.S., Seversky, E.V., 2004. The thermal environment of blocky materials in the mountains of Central Asia. Permafr. Periglac. Process. 15, 95–98. doi:10.1002/ppp.478

Haeberli,W., 1983. Frequency and characteristics of glacier floods in the Swiss Alps. Ann. Glaciol. 4, 85–90.

https://doi.org/10.3189/S0260305500005280.

Huggel, C., Salzmann, N., Allen, S., Caplan-Auerbach, J., Fischer, L., Haeberli, W., Larsen, C., Schneider, D., and Wessels, R.: Recent and future warm extreme events and highmountain slope stability, Philos. T. R. Soc. A, 368, 2435–2459, https://doi.org/10.1098/rsta.2010.0078, 2010.

Huggel, C., Khabarov, N., Korup, O., and Obersteiner, M.: Physical impacts of climate change on landslide occurrence and related adaptation, in: Landslides, Types, Mechanisms and Modelling, edited by: Clague, J. J. and Stead, D., Cambridge University Press, Cambridge UK, 121–133, 2012.

Hungr, O., Evans, S. G., Bovis, M. J., and Hutchinson, J. N.: A review of the classification of landslides of the flow type, Environ. Eng. Geosci., 7, 221–238, https://doi.org/10.2113/gseegeosci.7.3.221, 2001.

Hungr, O., Leroueil, S., and Picarelli, L.: The Varnes classification of landslide types, an update, Landslides, 11, 167–194, https://doi.org/10.1007/s10346-013-0436-y, 2014.

ICRC, 1998. Uzbekistan/Kyrgyzstan Floods. https: //reliefweb.int/report/kyrgyzstan/uzbekistankyrgyzstan-floods (accessed 17 October 2019).

Kapitsa, V., Shahgedanova, M., MacHguth, H., Severskiy, I., & Medeu, A. (2017). Assessment of evolution and risks of glacier lake outbursts in the Djungarskiy Alatau, Central Asia, using Landsat imagery and glacier bed topography modelling. *Natural Hazards and Earth System Sciences*, *17*(10), 1837–1856. https://doi.org/10.5194/nhess-17-1837-2017

Kronenberg, M., Machguth, H., Eichler, A., Schwikowski, M., & Hoelzle, M. (2021). Comparison of historical and recent accumulation rates on Abramov Glacier, Pamir Alay. *Journal of Glaciology*, *67*(262), 253–268. https://doi.org/10.1017/jog.2020.103

Kulmatov, R., Taylakov, A., & Khasanov, S. (2021). Investigating and evaluating the dynamics of change in water resources of the Aydar-Arnasay Lake system in Uzbekistan. *Environmental Science and Pollution Research*, *28*(10), 12245–12255. https://doi.org/10.1007/s11356-020-11959-7

Mamadjanova, G., Wild, S., Walz, M. A., & Leckebusch, G. C. (2018). The role of synoptic processes in mudflow formation in the piedmont areas of Uzbekistan. *Natural Hazards and Earth System Sciences*, *18*(11), 2893–2919. https://doi.org/10.5194/nhess-18-2893-2018

Marchenko, S. S., Gorbunov, A. P., & Romanovsky, V. E. (2007). Permafrost warming in the Tien Shan Mountains, Central Asia. *Global and Planetary Change*, *56*(3–4), 311–327. https://doi.org/10.1016/j.gloplacha.2006.07.023

Narama, C., Kääb, A., Duishonakunov, M., & Abdrakhmatov, K. (2009). Spatial variability of recent glacier area changes in the Tien Shan Mountains, Central Asia, using Corona (~ 1970), Landsat (~ 2000), and ALOS (~ 2007) satellite data. *Global and Planetary Change*, *71*(1–2), 42–54. https://doi.org/10.1016/j.gloplacha.2009.08.002

Narama, C., Severskiy, I., & Yegorov, A. (2009). Current state of Glacier Changes, Glacial Lakes, and Outburst Floods in the Ile Ala-Tau and Kungöry Ala.Too Ranges, Northern Tien Shan Mountains. *Geographical Studies*, *84*, 22–32.

Nikitin, A., 1987. Ozera Credney Azii. Gidrometeorologicheskiy regim ozer I vodohranilisch SSSR. Leningr. Gtdrometeoizdat 106.

Nikitin, A., Gorelkin, N., 1979. K voprosu gidrometeorologicheskogo obsnovaniya ekspluataii i ohrani vodnih resursov ozer i vodohranilish Sredney Azii. Ann. CARHRI 66, 3–9.

Petrakov, D. A., Chernomorets, S. S., Viskhadzhieva, K. S., Dokukin, M. D., Savernyuk, E. A., Petrov, M. A., Erokhin, S. A., Tutubalina, O. V., Glazyrin, G. E., Shpuntova, A. M., & Stoffel, M. (2020). Putting the poorly documented 1998 GLOF disaster in Shakhimardan River valley (Alay Range, Kyrgyzstan/Uzbekistan) into perspective. *Science of the Total Environment*, *724*, 138287. https://doi.org/10.1016/j.scitotenv.2020.138287

Petrov, M. A., Sabitov, T. Y., Tomashevskaya, I. G., Glazirin, G. E., Chernomorets, S. S., Savernyuk, E. A., Tutubalina, O. V., Petrakov, D. A., Sokolov, L. S., Dokukin, M. D., Mountrakis, G., Ruiz-Villanueva, V., & Stoffel, M. (2017). Glacial lake inventory and lake outburst potential in Uzbekistan. *Science of the Total*

Environment, *592*, 228–242. https://doi.org/10.1016/j.scitotenv.2017.03.068

Reuters, 1998. Death Toll in Uzbek Flood Hits 93, Could Go Higher. https://reliefweb.int/report/kyrgyzstan/death-toll-uzbek-flood-hits-93-could-go-higher, Accessed date: 17 October 2019.

Reyzvih, V., Kruglovskiy, G., Nikitin, A., 1971. Prichini I usloviya proriva oz. Yashinkul'. Jounral TGMO 4, 48–95.

Semakova, E., Gunasekara, K., & Semakov, D. (2015). Identification of the glaciers and mountain naturally dammed lakes in the Pskem, the Kashkadarya and the Surhandarya River basins, Uzbekistan, using ALOS satellite data. *Geomatics, Natural Hazards and Risk*, *7*(3), 1081–1098. https://doi.org/10.1080/19475705.2015.1023852

Shikhov, A. N., & Bykov, A. V. (2018). *Calculation of snow water equivalent on a large basin using global weather forecast models data*. *1*(367), 64–78.

Sidle, R. C. and Ochiai, H.: Landslides: processes, prediction, and land use, American Geophysical Union, Washington, DC, 312 pp., 2006.

Sorg, A., Bolch, T., Stoffel, M., Solomina, O., & Beniston, M. (2012). Climate change impacts on glaciers and runoff in Tien Shan (Central Asia). *Nature Climate Change*, *2*(10), 725–731. https://doi.org/10.1038/nclimate1592

Staviskiy, Y., Jukov, N., 1968. Nekotorie svedeniya ob ozerah Maliy I Bol'shoy Kulun. Journal FGMO 104–111.

Tomashevskaya IG, Koldaev AA. 2014. Geologicheskiy faktor formirovaniya zavalnih ozer (r. Aksu-Zapadnaya, bass. r. Kashkadaryi, Gissarskiy hrebet) [Geological factor of formation of landslide-dammed lakes (West-Aksu river, Kashkadarya river basin, Hissar ridge)]. Geol Mineral Resour. 1:60_63. Russian.

UNEP, 2007. Global outlook for ice and snow. UNEP, 235pp

Yakovlev, A., Batirov, R., 2003. Monitoring of mountain glaciers and glacial lakes using ASTER space images. First Int. Conf. Hydrol. Water Resour. Asia Pac. Reg., APHW 1042–1047.

Zaginaev, V., Ballesteros-Cánovas, J.A., Erokhin, S.,Matov, E., Petrakov, D., Stoffel,M., 2016. Reconstruction of glacial Lake outburst floods in northern Tien-Shan: implications for hazard assessment. Geomorphology 269, 75–84. https://doi.org/10.1016/j.geomorph.2016.06.028.

Zaginaev, V., Petrakov, D., Erokhin, S., Meleshko, A., Stoffel, M., Ballesteros-Cánovas, J.A., 2019. Geomorphic control on regional glacier lake outburst flood and debris flow activity over northern Tien Shan. Glob. Planet. Chang. 176, 5–59. https://doi.org/10.1016/j.gloplacha.2019.03.003.

Zheng, G., Bao, A., Li, J., Zhang, G., Xie, H., & Guo, H. (2019). Sustained growth of high mountain lakes in the headwaters of the Syr Darya River , Central Asia Sustained growth of high mountain lakes in the headwaters of the Syr Darya River , Central Asia. *Global and Planetary Change*, *176*(March), 84–99. https://doi.org/10.1016/j.gloplacha.2019.03.004