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Evaluation of Glacial Lakes and Catastrophic Floods on the Northern Slopes of the Kyrgyz Range

Dambaru Ballab Kattel[1] *, Ashutosh Mohanty[2], Mirlan Daiyrov[3], Weicai Wang[1], Manoranjan Mishra[4], Zheenbek Kulenbekov[5], and Binod Dawadi[6,7]

** Corresponding author: katteldb@gmail.com, katteldb@itpcas.ac.cn*

[1] Key Laboratory of Tibetan Plateau Environment and Land Surface Processes, Institute of Tibetan Plateau Research, Chinese Academy of Sciences, No. 16, Lincui Road, Chaoyang District, Beijing 100101, P.R. China
[2] Disaster Management and Climate Change Department, Shoolini University, Solan 173212, Himanchal Pradesh, India
[3] Central-Asian Institute for Applied Geosciences (CAIAG), Timur Frunze Road 73/2, 720027 Bishkek, Kyrgyz Republic
[4] Department of Natural Resources Management and Geo-informatics, Khallikote University, Berhampur, Odisha 768003, India
[5] Department of Applied Geology, American University of Central Asia, 7/6 Aaly Tokonbaev Street, 720060, Bishkek, Kyrgyz Republic
[6] Central Department of Hydrology and Meteorology, Tribhuvan University, Kathmandu, Nepal
[7] Kathmandu Center for Research and Education, Chinese Academy of Sciences–Tribhuvan University, Kathmandu, Nepal

The changing climate in the 20th and 21st centuries has had a profound impact on glacial lake formation and downwasting. The rapid receding of glaciers due to increased atmospheric temperature has caused glacial lake outburst floods (GLOFs) in the nival–glacial belt region on the northern slopes of the Kyrgyz mountain range over the last 20 years. Catastrophic events downstream due to GLOFs are increasing in this region and could affect the natural environment, human lives, and property. This study aims to evaluate the spatial distribution and growth of glacial lakes on the northern slopes of the Kyrgyz range using semiautomated remote sensing and field techniques. We recorded 273 glacial lakes and examined the characteristics of 5 small GLOFs that occurred between 2000 and 2012 due to moraine collapse. Further, the findings highlight alarmingly rapid changes and a high probability that these lakes will burst soon. Remote sensing, geographic information system, and statistical techniques combined with field-based knowledge are effective in identifying and monitoring the catastrophic nature of GLOFs on the northern slopes of the Kyrgyz range. The study recommends creating a spatial database inventory of both glacial lakes and GLOFs in the region using high-resolution satellite images and in-situ field techniques.

Keywords: *GIS; glacial lakes; glacial lake outburst floods; Kyrgyz range; remote sensing; river basin.*

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Introduction

Glacier-related floods, including glacial lake outburst floods (GLOFs), are well documented in almost all mountain ranges around the world, but the hazard characteristics of these fluctuating lakes are poorly recorded (Hock et al 2019; IPCC 2019). The northern slopes of the Kyrgyz range are frequently affected by GLOFs, landslides, and rainfall-induced mudflows (Blagoveshchenskiy and Yegorov 2009; Bolch et al 2011). GLOFs are the most dangerous of these and have been occurring repeatedly in this region recently. In particular, in the last decade, alpine GLOFs have been in the news due to their devastating impacts in both intensity and magnitude. Climate change appears to exacerbate the situation, resulting in a higher incidence of GLOFs, in addition to other hazards (Aryal 2012), in high mountain regions across the Third Pole (Yao et al 2019). Thus, sustainable development in the region is at risk from emerging and intensifying cryospheric changes (IPCC 2019).

Deglaciation is a major cause of the formation and growth of glacial lakes in the cryosphere region, including the Third Pole (Hock et al 2019). In response to global warming (eg Bhutiyani et al 2007; You et al 2010; Kattel and Yao 2013), the glaciers in this cryosphere region are receding faster than the global average (eg Aizen et al 2006, 2007; Li et al 2006; Liu et al 2006; Bolch 2007; Yao et al 2007, 2019; Hagg et al 2013). Further, there is loss of mass from ice sheets and glaciers, and there has been a significant increase of permafrost temperature over the past decade (Walther et al 2017; IPCC 2019). This unusual phenomenon of receding glaciers is resulting in a dramatic increase in the size and number of supraglacial (moraine-dammed) and proglacial lakes (Janský et al 2010; Westoby et al 2014; Hock et al 2019). Similar patterns are also observed across the northern and inner Tien Shan mountains (Janský et al 2010). Further, Aizen et al (2006) reported a reduction of about 14.2% of glaciers in the Tien Shan mountains over 60 years (1943–2003).

Snow cover, glaciers, and permafrost are projected to continue to decline in size in almost all regions throughout the 21st century because of increased air temperature (Qin 2002; Hock et al 2019). This will change the frequency,

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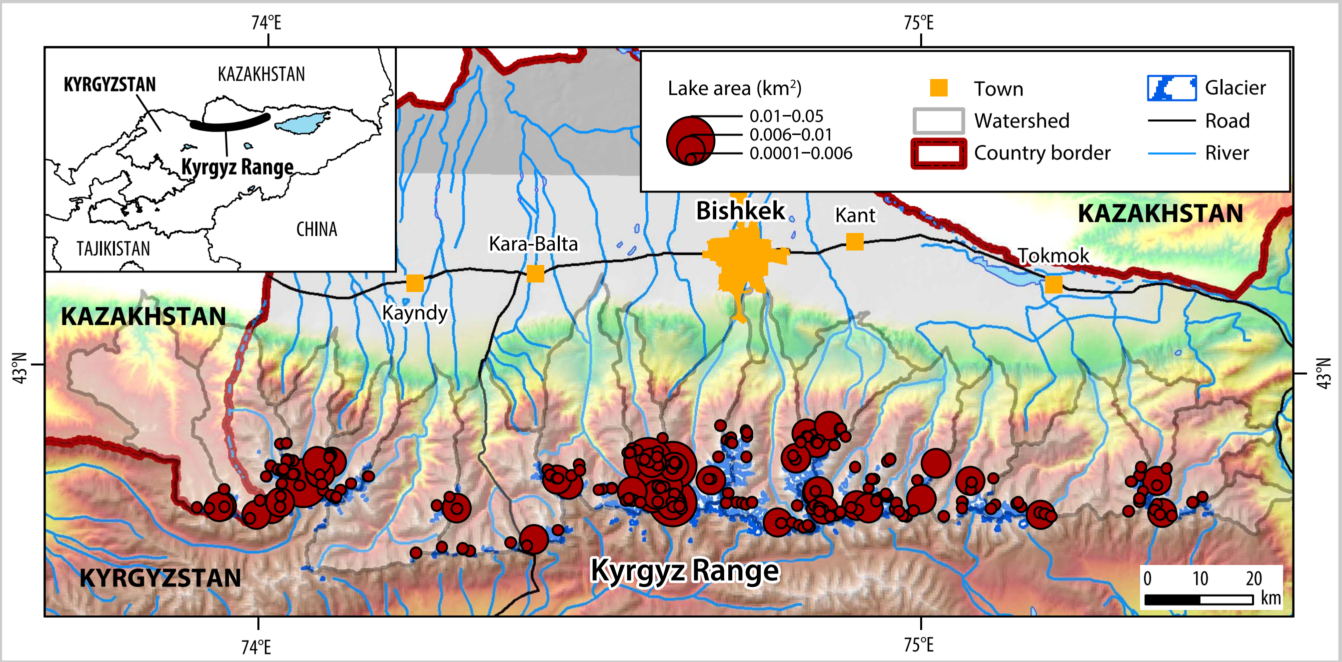
FIGURE 1 Study region and spatial distributions of the glacial lakes on the northern slopes of Kyrgyz range. (Data sources: *ALOS PRISM/AVNIR-2* from 2007 to 2010, *Landsat 7 ETM+* from 1999 to 2002, and *Landsat 8* in 2014)



intensity, and spatial distribution of glacial lake hazards, as the cryosphere continues to decline (IPCC 2019). Melting of glaciers and permafrost influences the hydrological regime of streams and can cause overfilling of high mountain lakes (Janský et al 2010; Shrestha et al 2010; Barros et al 2014; Field et al 2014) across the region. Generally, the retreat of glaciers and melting of permafrost will reduce the stability of slopes, and the number and area of glacial lakes will continue to increase, resulting in landslides and floods. Cascading events will also emerge where there is no record of glacial lake extreme events (Hock et al 2019). Outburst of mountain lakes and subsequent mudflows endanger settlements, roads, power lines, pipelines, agriculture, and pastures in downstream areas (Cook et al 2018). Therefore, frequent monitoring of alpine glaciers is required, and an understanding of the spatial pattern and phenomena of outbursts is crucial to prevent damage to property, infrastructure, and livelihoods.

A systematic study of mountain lakes in Kyrgyzstan has been carried out since 1966, when the catastrophic outburst of the obstructed Yashilkul lake occurred along the Isfairamsay river valley on 18 June (Rezvoi and Rezvoi 1969; Erohin and Cerny 2009). Grigoriev and Frolov (1966) were the first people to investigate historical changes in Koltor lake using bathymetric measurement techniques. Erokhin and Aleshin (1997) further investigated the status of this lake's dam. The characterization of morphology and regular monitoring of Adygene and Koltor glacial lakes were initiated by Janský et al (2009). With the help of the Czech experts, the Kyrgyzstan Ministry of Natural Resources built a high mountain scientific station at the Adygene glacial lake in 2008 to regularly monitor cryosphere parameters. This lake is located in the Ala-Archa river valley, at an elevation of 3600 masl. A team of international experts from the Research Institute of Science for Nature, Japan, the Central-Asian Institute for Applied Geosciences (CAIAG), and the State Geology Agency of the Kyrgyz Republic also have contributed to the investigation and generation of high-resolution photography of high mountain glacial lakes over the last decade.

Most relevant studies on the status of alpine glaciers and potential hazards of GLOF have been carried out in the Ala-Archa river basin, which is located on the northern slopes of the Kyrgyz range (Erokhin 2008). However, there has been little investigation and assessment of alpine glaciers and the potential hazards of lakes in the complex mountain system of Kyrgyzstan. The objective of the present study is to identify the spatial and temporal distribution of glacial lakes using remote sensing and global information system (GIS) data combined with field knowledge of the northern slopes of the Kyrgyz mountain range. In addition, we also evaluated the hazard potential and likelihood of GLOF events by reviewing literature and field information collected from a physical survey conducted in the study region. Finally, to identify lakes that pose a hazard, detailed analysis must be carried out using high-resolution satellite imagery and sophisticated techniques and tools in the future. The societal impacts of GLOFs are not within the scope of our study. The approach used in the study standardizes criteria and can be applied by researchers in developing countries to assess many glaciers in poorly accessible areas of the world.

Study area

The Kyrgyz range, which extends about 375 km from west to east, is one of the main chains of the northern Tien Shan mountains (Figure 1). Alamudun Peak, in the central part of the range, is its highest point, reaching an elevation of 4875 masl. The average height of the range lies between 2500 and 4000 masl along the east–west chain (Atlas of the Kirghiz SSR 1987). The range mainly consists of Proterozoic and Paleozoic magmatic and sedimentary rocks. Along the

TABLE 1 List of satellite images used in this study.

Satellite	Date
Landsat 8/OLI	7 Feb 14
ALOS PRISM/AVNIR-2	27 Aug 10
	19 Aug 08
	7 Sep 08
	17 Sep 07
Landsat 7 ETM+	16 Sep 99
	9 Feb 00
	23 Aug 02

Kyrgyz range there is an exposed Caledonian intrusion; however, there is a Hercynian intrusion too. In addition, there is some Ordovician–Silurian granitoid, particularly in the Sokuluk, Ala-Archa, and Issyk-Ata massifs.

The complex mountainous terrain in the region has a significant impact on the weather and climate (Academy of Sciences of the Kyrgyz SSR 1965). The climate of these mountain systems is extreme continental. With increasing altitude, the temperature decreases, and the amount of precipitation increases (Narama, Kääb, et al 2010). The average annual temperature in July ranges from 12.3°C to 1.8°C between 2500 and 4000 masl (Podrezov 2013). January is the coldest, with temperatures between −9.4°C and −15.4°C.

The distribution of precipitation on the northern slopes of the Kyrgyz range is determined primarily by the orientation of the mountain slopes. Most of the precipitation falls in the middle and lower part of range and varies from 500 to 925 mm per year. The greatest amount of precipitation was observed at the Too-Ashu (718 mm) and Ala-Archa weather stations during June; these stations are located at 3225 masl and 2953 masl, respectively (Ponomarenko 1976). In general, the highest precipitation occurs between May and August in the region.

Along the Kyrgyz mountain range, most glaciers are found in the northern Tien Shan region. They generally accumulate in the spring season during May to August, when the most precipitation falls. In addition, changes in snow and glaciers have also changed the amount and seasonality of overflow in snow-dominated and glacier-fed river basins, with local impacts on water resources, among other issues (IPCC 2019). Almost all river basins in the Kyrgyz range are fed by snow and glacier meltwaters of the Tien Shan mountains (Aizen et al 2000; Usupaev et al 2015), which are highly sensitive to regional climate change.

Research methods

Remote sensing and geographic information systems (GISs) were used to investigate the characteristics of alpine glacial lakes on the northern slopes of the Kyrgyz range. The location of the study regions and the spatial distributions of the glacial lakes are presented in Figure 1. The inventory of glaciers was mapped using digital elevation model (DEM) data. These data were built using pan-sharpened data from the radiometer ASTER DEM. The vertical resolution of the retrieved DEM data was 30 m. Further, to identify the glacial lakes, satellite images from *ALOS PRISM/AVNIR-2* of 2007–2010, *Landsat 7 ETM+* of 1999–2002, and *Landsat 8* of 2014 were used.

In this study, 2014 summer season images from the *Landsat 8/OLI* satellite were used to develop a glacial lakes inventory. The image resolution of this source is 15 m, which is enough to extract a lake area of 0.0009 km^2. Table 1 presents more detailed information on the data used in this study. Further, *ALOS PRISM/AVNIR-2* 2007–2010 data were used to measure the sizes and elevations of glacial lakes. To extract the lake areas more clearly and to detect small lakes ($\sim$0.0009 km^2), we used *Landsat/OLI* image band 8, combined with bands 4, 5, and 6. We then pan-sharpened the images in Geomatics PCI to delineate the area of lakes in the 6-5-4 RGB band. There is no criterion for the threshold size of glacial lakes, as it varies among studies. The threshold of 0.003 km^2 in TM/ETM+ images was used to map glacial lakes based on satellite images (Gardelle et al 2011, 2013).

The lake areas for this study were extracted within debris landforms at the glacier fronts; lakes outside of Little Ice Age moraines were not included. The boundaries of lakes and glaciers were digitized manually using the ArcGIS 10 platform to compile polygon data for the glacial lakes ($>$0.001 km^2). To ensure the accuracy of the area of small lakes, *ALOS PRISM/AVNIR-2* (2007–2010) satellite images were used. The uncertainty of glacial lake areas was estimated using the lake's perimeter and the linear error (Fujita et al 2009; Zhang et al 2015; Nie et al 2017). An error of ± 0.5 pixels was utilized to calculate the uncertainty of glacial lakes areas, as suggested by Salerno et al (2012). Dynamic cross-validations were performed using high-resolution satellite imagery and field knowledge.

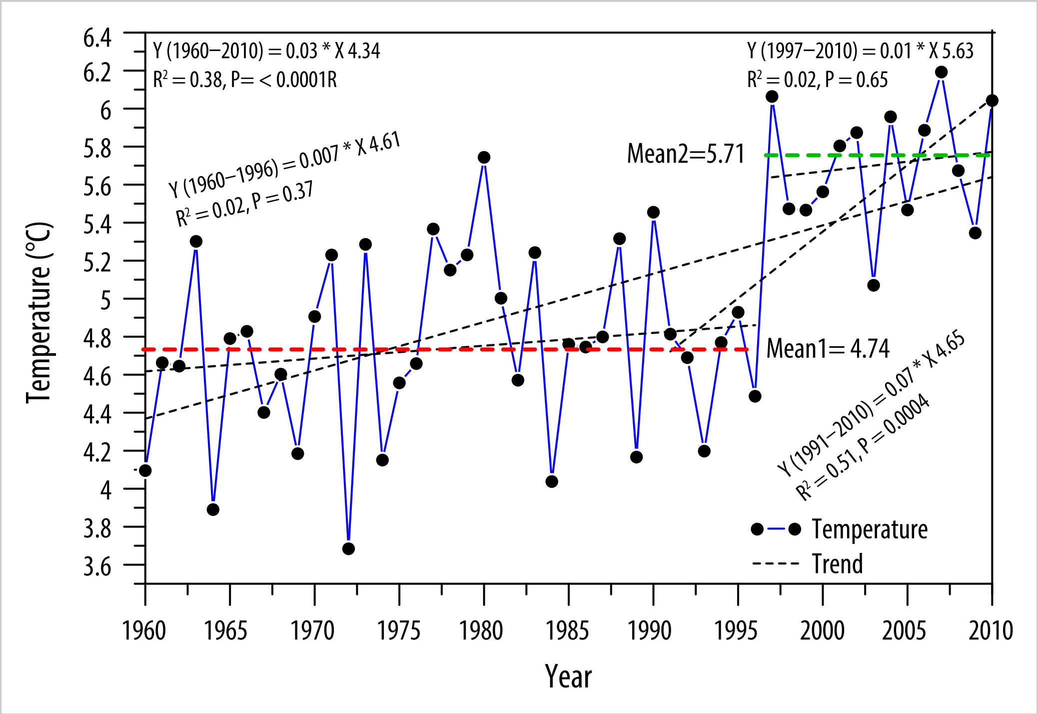
In this study, we investigated potentially dangerous lakes based on lake area expansions, drawing on findings from earlier studies of phenomena such as (1) underground channel development in ice dams, (2) continuously filling lakes or area expansions, and (3) water seepage from or through an ice dam (eg Erokhin and Aleshin 1997; Erokhin 2008; Janský et al 2010). Furthermore, we evaluated climatic trends, particularly in temperature, based on in-situ observation from 1960 to 2010, to explain the relationship between warming and the increasing number of glacial lakes and catastrophic floods in the study region. Climatic data were extracted from the climate profile of the Kyrgyz Republic, and the traditional linear regression method was applied to examine the trends.

Results and discussion

Climatic trends

Several studies have reported that the glaciers and permafrost along the Kyrgyz mountain ranges have been declining at a rapid pace due to increasing air temperature, induced by anthropogenic greenhouse gases. The rate of warming has been considerably higher in the last few decades (Bolch 2007; Giese et al 2007; Hu et al 2014). In addition to stimulating substantial glacier retreat, the rising air temperatures have increased evapotranspiration, aggravating water shortages (Siegfried et al 2012; Sorg et al 2012).

FIGURE 2 Interannual variation in temperature over the territory of Kyrgyz Republic from 1960 to 2010.



A recent investigation found that permafrost in High Mountain Asia, and in 28 other mountain regions across the globe, warmed by an average of 0.9 ± 0.05°C per decade between 2007 and 2016 (Biskaborn et al 2019). Observations in the Tien Shan and the Tibetan Plateau show general warming over a longer period (Hock et al 2019). The multiple datasets showed significant regional surface air temperature increase over the past 3 decades (1979–2011) in various parts of Central Asia of between 0.36 and 0.42°C per decade (Hu et al 2014). Warming is reported to be most prominent in the spring season (0.64–0.81°C per decade). With the exception of winter, other seasons have also shown significant warming during that period throughout Central Asian countries.

Across the Central Asian countries, the strong warming in spring was reported to have increased the risk of natural hazards in major rivers, especially from flooding and from outburst of ice dams and glacial lakes (Michael 2011; Siegfried et al 2012). Interannual variation in temperature over the territory of the Kyrgyz Republic is illustrated in Figure 2, based on data from the Kyrgyz Republic climate profile. It shows a similar pattern to that of regional climate variability. The temperature shows an increasing trend of 0.25°C per decade from 1960 to 2010. However, the trend is dramatically higher from1990 to 2010 (0.70°C per decade) than from 1960 to 1989 (0.12°C per decade).

The mass loss due to anthropogenic interference of glaciers worldwide, apart from Greenland and Antarctica, shows increasing trends from 25 ± 35% (1851–2010) to 69 ± 24% (1991–2010) (Marzeion et al 2014). According to Giese et al (2007), the temperature has increased by about 0.8°C per century between 1900–2000 and 2.0°C per century between 1950–2000 in the northern Tien Shan mountains. However, the abrupt reduction of snow accumulation in the Tien Shan mountains is due to changes in planetary circulation in the North Atlantic and North Pacific since the 1970s (Marzaion et al 2014; Hock et al 2019).

Spatiotemporal distribution of glacial lakes

The spatial distribution and number of identified glacial lakes in different basins are presented in Figures 1 and 3. Mass change of glaciers has been observed in most mountain regions. Regionally averaged mass budgets were least negative in High Mountain Asia (–150 ± 110 kg/m^2 per year), but variations within regions are strong in the period from 2000 to 2015 (Brun et al 2017; Hock et al 2019). In this study, we found that most alpine lakes on the northern slopes of the Kyrgyz range are situated in the Issyk-Ata, Sokuluk, Alamudun, and Ala-Archa river basins (Figure 3), and the majority of these basins are glacierized areas. The Issyk-Ata river basin has the highest number of alpine glacial lakes, numbering 48 (Figure 3). The types and area of alpine lakes in the Issyk-Ata river basin are highlighted in Table 2. The spatial distribution of glacial lakes in this basin is presented in Figure 3B.

The distribution of glacial lakes with respect to elevation in the study regions is shown in Figure 4A. The alpine lakes on the northern slopes of the Kyrgyz range are located between 3100 and 3800 masl, most of them (82%) being in the elevation range from 3400 to 3600 masl (Figure 4A). The primary factor determining the location of most alpine lakes at these elevations is the relief. The vertical profile of a typical glacial lake in the study region is presented in Figure 4B. At an altitude of 3400–3600 masl, the relief is relatively even due to the formation of moraines from the retreating glacier (ie the inclination is gradual; see Figure 4B). This creates favorable conditions for the appearance and development of glacial lakes. At an altitude above 3800 masl

FIGURE 3 (A) Numbers of identified glacial lakes in different basins; (B) the spatial distribution of glacial lake in Issyk-Ata river basin.

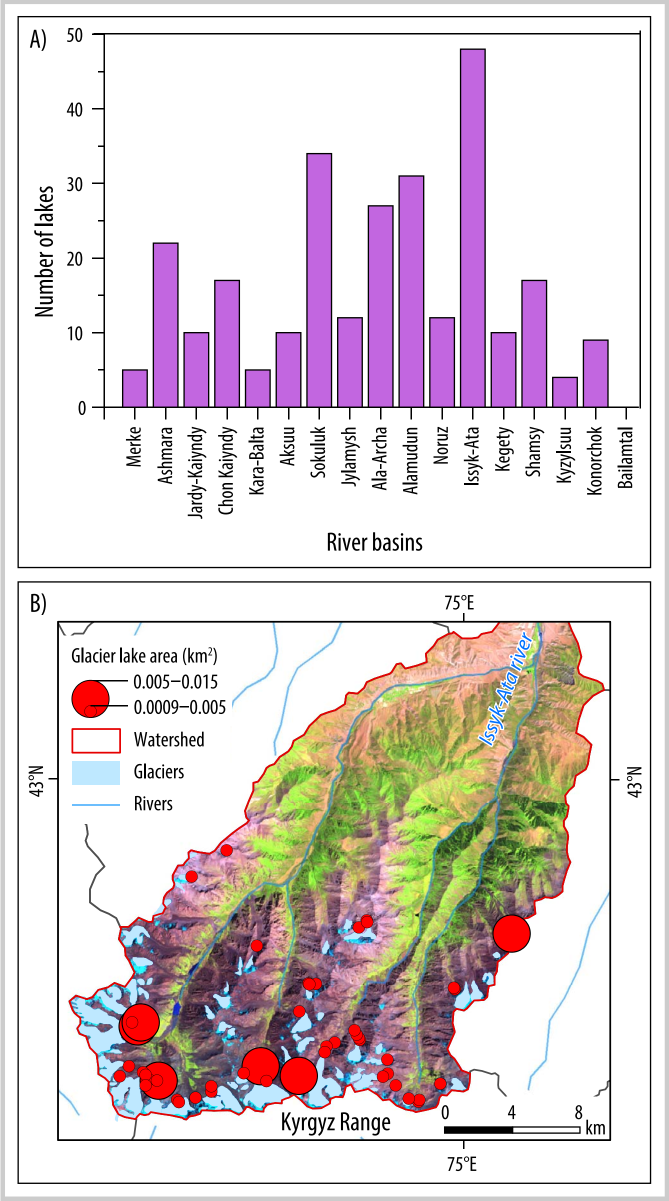
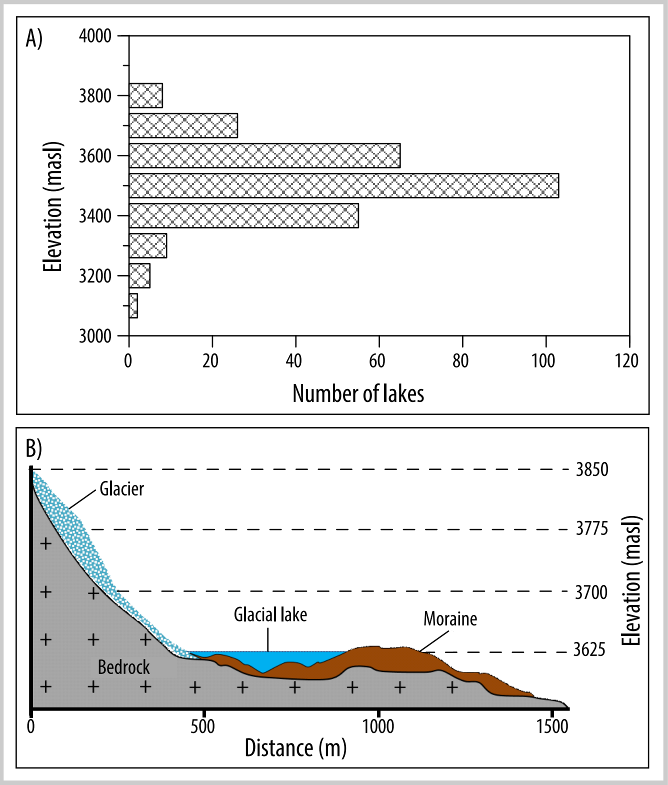


FIGURE 4 (A) The distribution of glacial lakes with respect to elevation; (B) the vertical profile of typical glacial lake on the northern slopes of the Kyrgyz range.



and below 3500 masl, lakes rarely appear due to the absence of moraine complexes (Figure 4).

The number and area of glacial lakes have increased in most regions in recent decades (Hock et al 2019). Climate change has played a critical role in the formation of glacial lakes, with a considerable increase in glacial lake area in high mountain regions, where the hazards from moraine- and ice-dammed lakes continue to increase (Gardelle et al 2011; Field et al 2014; Walther et al 2017). Lake systems often develop on the surface of downwasting, low-slope glaciers, where they coalesce from temporally variable supraglacial lakes (Benn et al 2012; Narama et al 2017; Hock et al 2019). Different scientific sources have reported about 2000 glacial lakes in Kyrgyzstan (eg Erohin and Cerny 2009; Janský et al 2010). From a combination of geospatial technology, field inventories, and historical records, we identified 273 alpine glacial lakes in the study area in 2014; of these, 220 were small ($>$0.001–0.005 km^2) (Figure 3A). Koltor is the largest lake, with an area of 0.23 km^2 (Janský et al 2010). It is situated in the valley of the Koltor river just next to its tributary, the Kegety river.

Glacial lakes outburst floods (GLOFs)

Glacial lake outburst floods (GLOFs) refer exclusively to sudden-onset outburst floods, which arise from a dam failure in moraine- or ice-dam lakes. They can be a major threat in high mountain areas (Khanal et al 2015; Richardson and Reynolds 2000). According to Richardson and Reynolds (2000), moraine- or ice-dam lakes are weak in nature, and, if they are suddenly filled up, the increasing hydrostatic pressure can cause the dam to burst, releasing significant volumes of water downstream. This effect can also be initiated by earthquakes, volcanic eruptions, or rock fall. The output is debris-filled floods moving downstream at a high velocity, threatening life and damaging property and livelihoods (Liu et al 2014; Khanal et al 2015). However, the size and velocity of the flood wave depend upon the amount of water released, debris load, breach characteristics, and slope of the region (Shrestha et al 2010).

In this study, a brief evaluation of this phenomenon in the region was undertaken, based on different sources. Of 328 lakes in the Kyrgyz territory, 12 are considered very dangerous, 21 dangerous, and the rest less dangerous (Erohin and Cerny 2009). On the northern slopes of the Kyrgyz range, out of 194 glacial lakes, 6 are considered as potentially dangerous (Erokhin 2008). Here Erokhin (2008) did not include the lakes whose area was less than 0.001 km^2. Due to

TABLE 2 Types and area of alpine lakes in Issyk-Ata river basin. (Table continued on next page.)

No.	Type of lake	Area (km^2)	Source	Elevation (masl)
1	Glacier-uncontacted	0.0004	*ALOS_AVNIR-2*	3811
2	Glacier-contacted	0.0009	*ALOS_AVNIR-2*	3883
3	Glacier-uncontacted	0.0033	*ALOS_AVNIR-2*	3528
4	Glacier-uncontacted	0.0128	*ALOS_AVNIR-2*	3481
5	Glacier-uncontacted	0.0010	*ALOS_AVNIR-2/PRISM_pans*	3605
6	Glacier-uncontacted	0.0017	*ALOS_AVNIR-2*	3768
7	Glacier-uncontacted	0.0011	*ALOS_AVNIR-2*	3533
8	Glacier-uncontacted	0.0005	*ALOS_AVNIR-2*	3698
9	Glacier-uncontacted	0.0014	*ALOS_AVNIR-2*	3655
10	Glacier-uncontacted	0.0011	*ALOS_AVNIR-2*	3592
11	Glacier-uncontacted	0.0007	*ALOS_AVNIR-2*	3687
12	Glacier-uncontacted	0.0003	*ALOS_AVNIR-2*	3591
13	Glacier-uncontacted	0.0103	*ALOS_AVNIR-2*	3580
14	Glacier-uncontacted	0.0140	*ALOS_AVNIR-2*	3562
15	Glacier-uncontacted	0.0013	*ALOS_AVNIR-2*	3622
16	Glacier-contacted	0.0008	*ALOS_AVNIR-2*	3673
17	Glacier-uncontacted	0.0059	*ALOS_AVNIR-2*	3537
18	Glacier-uncontacted	0.0010	*ALOS_AVNIR-2/PRISM_pans*	3658
19	Glacier-uncontacted	0.0018	*ALOS_AVNIR-2*	3513
20	Glacier-uncontacted	0.0010	*ALOS_AVNIR-2*	3537
21	Glacier-uncontacted	0.0010	*ALOS_AVNIR-2/PRISM_pans*	3647
22	Glacier-uncontacted	0.0007	*ALOS_AVNIR-2/PRISM_pans*	3608
23	Glacier-uncontacted	0.0005	*ALOS_AVNIR-2/PRISM_pans*	3561
24	Glacier-uncontacted	0.0040	*ALOS_AVNIR-2*	3707
25	Glacier-uncontacted	0.0021	*ALOS_AVNIR-2*	3573
26	Glacier-contacted	0.0043	*ALOS_AVNIR-2*	3830
27	Glacier-uncontacted	0.0086	*ALOS_AVNIR-2*	3475
28	Glacier-uncontacted	0.0155	*ALOS_AVNIR-2*	3496
29	Glacier-uncontacted	0.0113	*ALOS_AVNIR-2*	3854
30	Glacier-uncontacted	0.0034	*ALOS_AVNIR-2*	3673
31	Glacier-uncontacted	0.0014	*ALOS_AVNIR-2*	3695
32	Glacier-uncontacted	0.0028	*ALOS_AVNIR-2*	3567
33	Glacier-contacted	0.0008	*ALOS_AVNIR-2*	3731
34	Glacier-uncontacted	0.0005	*ALOS_AVNIR-2*	3660
35	Glacier-uncontacted	0.0035	*ALOS_AVNIR-2*	3598
36	Glacier-uncontacted	0.0022	*ALOS_AVNIR-2*	3482
37	Glacier-contacted	0.0013	*ALOS_AVNIR-2*	3728
38	Glacier-contacted	0.0019	*ALOS_AVNIR-2*	3636

TABLE 2 Continued. (First part of Table 2 on previous page.)

No.	Type of lake	Area (km^2)	Source	Elevation (masl)
39	Glacier-uncontacted	0.0036	*ALOS_AVNIR-2*	3656
40	Glacier-uncontacted	0.0031	*ALOS_AVNIR-2*	3648
41	Glacier-uncontacted	0.0024	*ALOS_AVNIR-2*	3589
42	Glacier-uncontacted	0.0019	*ALOS_AVNIR-2*	3623
43	Glacier-uncontacted	0.0007	*ALOS_AVNIR-2*	3610
44	Glacier-contacted	0.0008	*ALOS_AVNIR-2*	3686
45	Glacier-uncontacted	0.0017	*ALOS_AVNIR-2*	3575
46	Glacier-contacted	0.0041	*ALOS_AVNIR-2*	3549
47	Glacier-uncontacted	0.0011	*ALOS_AVNIR-2*	3586
48	Glacier-uncontacted	0.0016	*ALOS_AVNIR-2*	3580

rapid melting of glaciers in the last decades as a result of rising temperatures (Figure 2), the water surface area of most of the glacial lakes in the region has increased dramatically (eg Table 2). The largest moraine-glacial lake, Petrov, is the best example, providing physical evidence of the recent impact of global warming. The frontal part of this lake glacier tongue has been retreating 50–65 m annually during the last decade (Janský et al 2009).

Status reports of the Kyrgyz Hydro-meteorological Services and the Ministry of Emergency Situations of Kyrgyzstan and other research (eg Erohin and Cerny 2009; Janský et al 2010) have documented about 70 cases of disastrous lake outburst events since 1950. The largest discharges from GLOFs were registered in the Ala-Archa and Sokuluk river basins. An increase in glacier melting could be responsible for the catastrophic consequences. A study by Aizen et al (2006) reported that the area of Ala-Archa glacier shrank by 5.1% from 1943 to 1977 and by 10.6% from 1977 to 2003, supporting this suggestion. Similar rates of shrinkage have also occurred in the Golubina glacier of the Ala-Archa river basin (Aizen 1988).

The number of GLOF events recorded between 1950 and 2013 in various basins is presented in Figure 5A. The figure shows that the highest number of GLOF events was recorded in the Ala-Archa river basin. The greatest amount of runoff (400 m^3/s) over the same period was also recorded in this basin. In recent decades, the risk of outburst of glacial lakes in the study region has increased significantly. Changes in local parameters of climatic variables, especially temperature (Figure 2), followed by rapid retreat of glaciers could be the cause of the frequent GLOF events in the region. Physical evidence is provided by the outburst of Zyndan lake on 24 July 2008 (Narama, Duishonakunov, et al 2010) and of Tez-Tor lake in 2012 (Karamoldoev and Daiyrov 2012) as a result of moraine collapse (Narama, Duishonakunov, et al 2010; Narama et al 2018). Three people died, and bridges, houses, and infrastructure were damaged by the Zyndan GLOF event (Narama, Duishonakunov, et al 2010). However, knowledge about damage from these GLOF events remains incomplete.

Furthermore, changes in the shoreline of the Keidykuchkach glacial lake over the last 35 years, shown in Figure 5B, confirm the effect of climatic warming on the retreat of mountain glaciers. The figure shows a dramatic difference in lake area between 1978 and 2013, as well as a significant reduction in glacier area over the same period. The greatest rate of increase (0.07°C per year) of air temperature in the Kyrgyz territory between 1990 and 2010 (Figure 2) likewise supports the result.

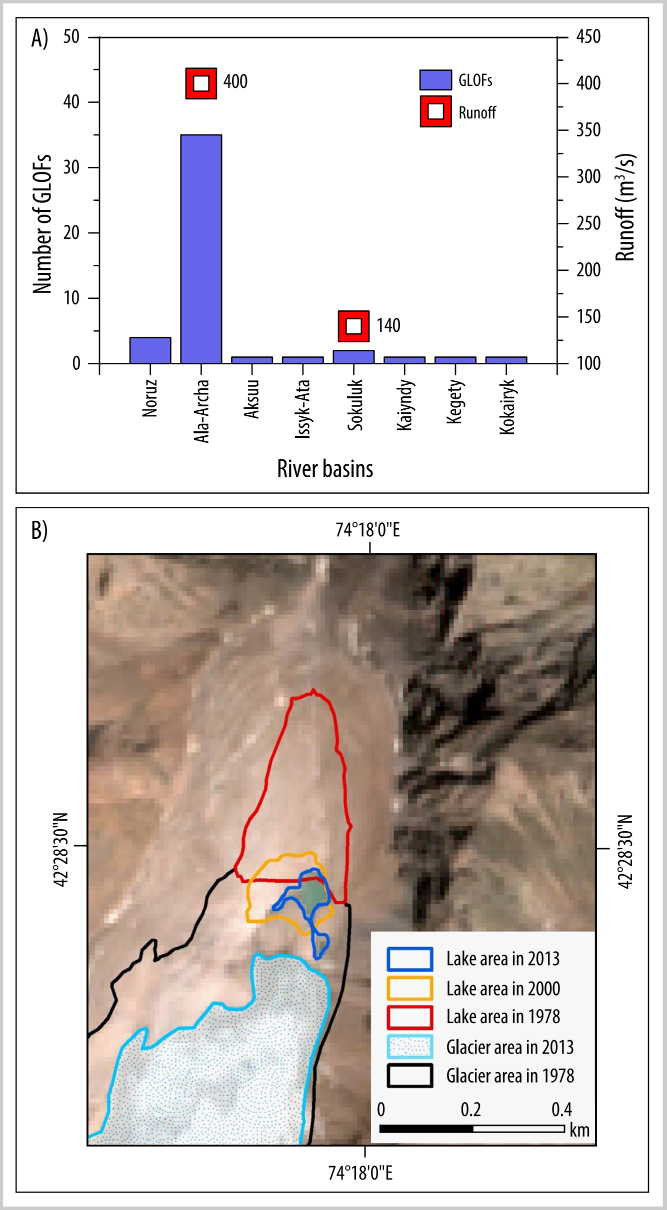
The Ministry of Emergency Situations of Kyrgyzstan also reports that the GLOF events in the 1960s, 1970s, and 1980s brought significant economic loss and damaged infrastructure downstream on the southern slopes of the Kyrgyz range. In the Sokuluk river basin, two GLOFs occurred in 1983 and 1989 (Figure 5A). The GLOF-induced debris flow in 1983 was more devastating than that in 1989. It released 300,000 m^3 water out of the glacial lake and caused significant damage to the national economy. The runoff recorded in this river basin during the 1983 event was 140 m^3/s (Figure 5A).

Researchers working in this area have reported that moraine-glacial lakes pose the greatest threat to the socioeconomic stability of the region (Erohin and Cerny 2009; Janský et al 2010). The moraine-glacial type of lake develops in moraine depressions after the retreat of glaciers (eg Figure 4B). The bottom and the slopes of the lake basins mainly develop from ice and frozen debris (Janský et al 2010). The majority of GLOFs in these areas, such as Tez-Tor (2012) (Karamoldoev and Daiyrov 2012; Erokhin et al 2017), Zyndan (24 July 2008) (Narama et al 2018), and Takyr-Tor (2009), were the result of moraine collapse.

Field survey and satellite images analysis of Takyr-Tor glacial lake

As we have already discussed, several observations in the Third Pole region show a warming trend and increasing temperature extremes, as well as declining mountain glaciers and intensively thawing permafrost (Field et al 2012; Hock et al 2019; Yao et al 2019). The ongoing retreat of glaciers in this region is associated with the warming atmosphere (Shrestha et al 2010). The situation is similar in the Kyrgyz territory. Several studies have suggested that the glaciers along the Kyrgyz mountain range have been retreating intensively over the last few decades. A study by Ershova

FIGURE 5 (A) The number of GLOF events recorded between 1950 and 2013 in different basins; (B) changes in the shoreline of Keidykuchkach glacial lake in the 35 years from 1978 to 2013.



(2007) showed that the total glaciated area has decreased by ∼28% between 1963 and 2000. She also reported that 8 glaciers have completely disappeared.

According to a study by Bolch (2015) in the Ala-Archa basin, glaciers retreated by 18% between 1964 and 2010. Although deglaciation due to temperature rise has many consequences, the formation of glacial lakes surrounded by fragile and weak moraine sediment is the most tangible effect. Further, the shrinkage in area of glacial formation results in the formation of lakes across the world's high mountain regions (Buckel et al 2018; Hock et al 2019). Expansion or formation of glacial lakes from snow melting at the terminus of the receding glacier increases the chances that GLOFs will occur (Barros et al 2014; Field et al 2014), with the potential to catastrophically affect the lives, property, and livelihoods of the population living downstream (Shrestha et al 2010).

The degradation of permafrost and the melting of ice buried in lake dams have lowered dam stability and contributed to outburst floods in many high mountain regions (Fujita et al 2013; Erokhin et al 2017; Narama et al 2017; Hock et al 2019). In this study, we conducted a field investigation to identify the cause of the Takyr-Tor GLOF in 2009. The change in area of Takyr-Tor lake after the outburst is illustrated in Figure 6. A GLOF had also occurred in this lake on 5 June 1992; however, the causes and casualties of this GLOF event are not known.

Takyr-Tor lake is located at latitude 74.82°N and longitude 42.57°E in the Noruz river basin, at an elevation of 3569 masl (Figure 6A). A field investigation and physical base survey were conducted on the ground and combined with remote-sensing observations and in-depth analysis of the area where the debris flows occurred (Figure 6B, C). The shoreline of the lake was determined using an RTK-GPS900 (Leica Geosystems). RTK-GPS 900 and *Landsat 7 ETM+* images were used to survey the extent of the flood area (Figure 6A). Furthermore, calculation of volumes and mapping of deformation of the bottom of the lake were developed using MapInfo 7 and ArcGIS 10.

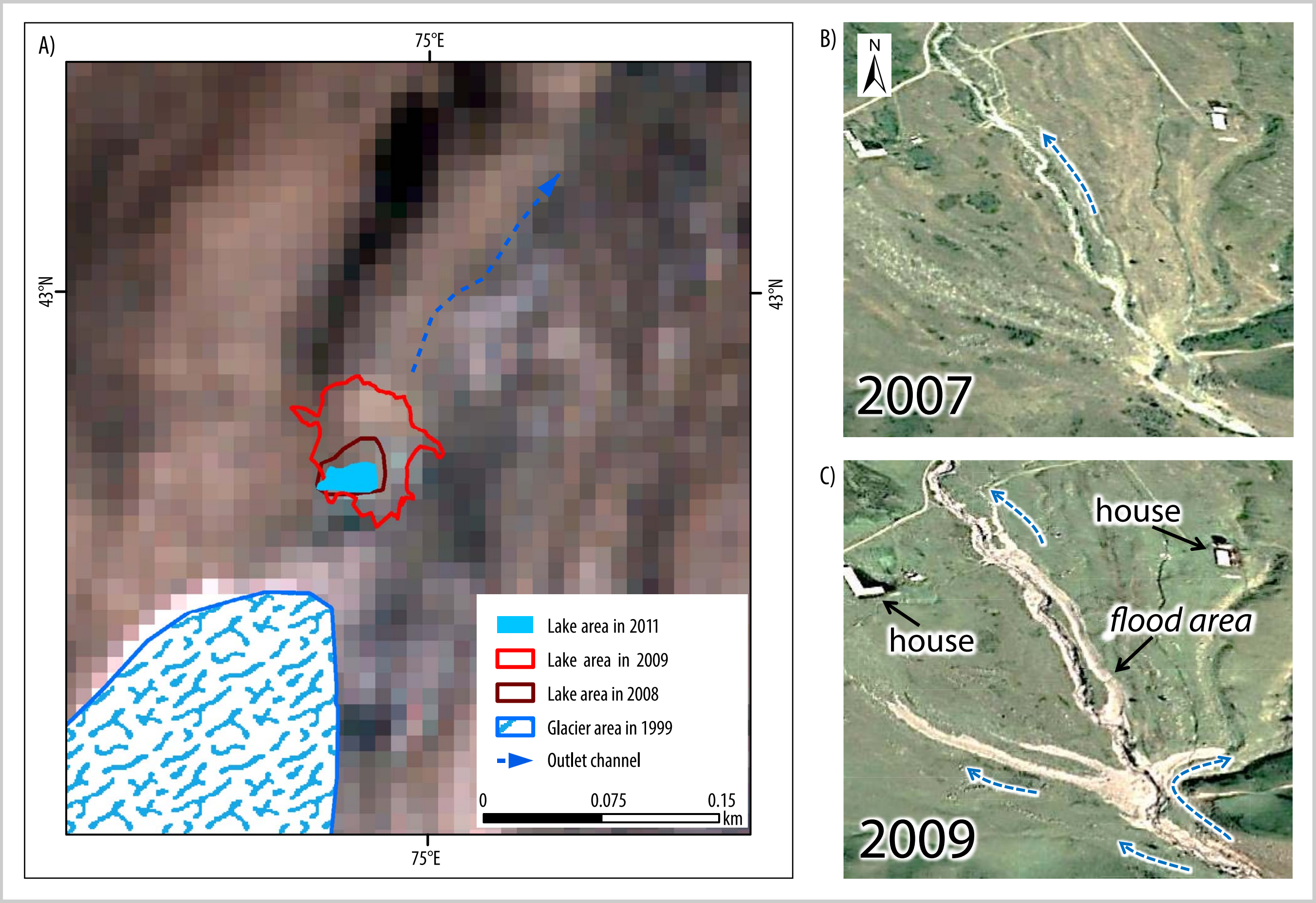
The glacier area attached to the lake, in comparison to 1999 or earlier, has been converted into debris, due to the retreating ice. Dramatic changes in the shoreline of the lake occurred between 2008 and 2011 (Figure 6A). Compared to 2008, the area of the lake was significantly reduced in 2011 as a result of the GLOF in 2009. The outburst water, mixed with moraine, gradually formed a debris flow along its flow route. GPS and bathymetric survey data show that the lake area before outburst was 0.007 km^2, declining to 0.0006 km^2 after the event (Figure 6A). The lake volume was 20,829 m^3 before the outburst.

The results from this investigation further suggest that the lake outburst was caused by the collapse of the glacier tongue and the failure of the moraine dam due to melting of dead ice underneath, as a result of high temperatures in recent decades (Figure 2). Hence, it can be concluded that the shrinkage of glaciers and formation and expansion of alpine lakes in the northern parts of the Tien Shan mountains are correlated with changing climate, as stated by Bolch et al (2011).

Conclusions

In this study, we evaluated the spatial distribution and growth of glacial lakes on the northern slopes of the Kyrgyz mountain range. The study confirmed and developed 273 glacial lake inventories from the northern slopes of the Kyrgyz range, based on interpretation of in-situ photos, multitemporal satellite images, and topographic maps. Most of these small lakes have formed since 1990 due to a rise in temperature. The rapid growth in size and number of lakes associated with the receding of glaciers due to climatic variability could lead to catastrophic floods in coming days. Historical records show that glacial lakes are more concentrated in the middle and western parts of the range. Further, field investigation recorded signs of 5 small GLOFs between 2000 and 2012. The field investigation also showed that the majority of past GLOF events were associated with

FIGURE 6 (A) Change of Takyr-Tor lake area before and after the outburst; (B) debris flow in 2007; (C) debris flows in 2009.



moraine collapse. The spatiotemporal spread of glacial lakes with potential for outburst and floods in the north of the Kyrgyz range is alarming and should be addressed by policy- and decision makers. This study also highlighted that the recent outburst of Takyr-Tor lake is associated with the collapse of the glacier tongue and the melting of dead ice beneath the moraine dam. There is an urgent need to create a spatial database inventory of glacial lakes using remote sensing and GIS technology validated with field data. This could help planners and policymakers in reconstructing and understanding glacial lake development in this region.

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