Monitoring the Development of Potential Hazardous Mountain Lakes Using Remote Sensing in the Kyrgyz Republic

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Abstract
The Kyrgyz Republic is a high mountainous country with a high risk of development of debris and mudflows, landslide and other natural hazards. One of such hazards is outbursts of high-mountain lakes (GLOF), which occur much less frequently than debris and mudflows of stormwater genesis and from snowmelt. The hazard of GLOFs in the Kyrgyz Republic is a significant concern due to the region's topography, climate, and the presence of numerous glacier-fed lakes. However, debris flows caused by GLOF are characterized by their catastrophic nature. To monitor and control the development of hazardous lakes, a specialized catalog was created and is used by Ministry of Emergency Situations of KR (MES KR). This catalog is dynamic and requires modern methods and technical solutions for prompt input of information. At present, the catalog of outburst lakes contains 370 lakes, which are assigned different categories of outburst hazard. Most of the outburst lakes are in inaccessible areas, which makes it difficult to survey. During the summer, hiking expeditions with bathymetric measurements are conducted on the most hazardous lakes. To improve the system of monitoring and forecasting of outburst lakes, a tool for monitoring high mountain lakes was created and integrated into the national monitoring system of the MES KR using Google Earth Engine algorithms and scripts, as well as open sources data of meteorological information. The NDWI index calculated from publicly available Sentinel-2 and Landsat-8,9 images and used to detect changes in lake area. The images of all lakes are downloaded in automatic mode, and a shapefile is created for each lake based on the index. Subsequently, all shapefiles are compared with previous measurements, resulting in reports indicating the increase or decrease of areas. Additionally, all meteorological information obtained from satellite data services is also available in the system. This information system will enhance the system of monitoring and forecasting of GLOF.

Keywords: GLOF, High Mountain Lakes, Information System, Satellite Images, Temporal Distribution

1. Introduction

GLOFs are potentially devastating events that occur when glacial lakes, often dammed by ice or ice cored moraine, suddenly release large volumes of water, debris, and sediment, leading to downstream flooding [1] and [2]. The failure of natural dams may cause large outburst floods and debris flows, what present the greatest threat to people and property. These phenomena have been largely described in all large mountain ranges around the world: in the Tien-Shan [3][4][5] and [6], the Alps [7], the Himalayas [8] and [9]. In recent years, global databases of GLOFs have been created with outbursts locations [10] and [11]. Furthermore, country-specific and river basin-specific inventories of high-elevation lake outbursts have been conducted for High-Mountain Asia (HMA) and Central Asia (CA) [12][13][14] and [15].

Considering the observed degradation of the Tien-Shan glaciation [16] and the documented shifts in climate patterns in the high mountain zone [17], there is a clear need for continuous monitoring of cryosphere development, including the emergence of potential hazardous lakes [18]. According to previous studies there are more than 2000 lakes over the territory of Kyrgyzstan [19]. Most of lakes were formed in flat topography, and have rock dams, or formed in deep depressions and impounded by thick stable layers of ancient ice-free moraines or heavy landslide layers, which are referred to as not susceptible to outburst lakes [20] and [21]. Yet, some of them have weak dams containing ice cores or composed of loose fragmented material and are potentially dangerous in case of self-destruction of dams caused by different initial mechanisms [8][22][23] and [24].

Since 1846, registered 197 outburst [11] events have been occurred in Kyrgyzstan, what is on the average 1 event per year. This number includes the annual outburst floods from a unique glacier dammed Merzbacher lake formed between the north and south Inylchek Glaciers in central Tien Shan, which drains at least once per year [25]. Fifty percent of outburst floods (35 events) were precisely documented in reports and literature and are known from our own field investigations, and most of them caused catastrophic consequences, human and property losses. Among them 92 outburst events were caused by failure of moraine-dammed lakes (moraine dams containing ice cores), 88 from ice-dammed lakes, and 2 large floods from landslide-dammed lakes [20] other outbursts (18) from Aksay Glacier water pocket [4].

The history of regular research of the high mountain lakes of the Kyrgyz Tien-Shan, begins with the catastrophic dam failure of landslide-dammed lake Yashilkul on June 18, 1966. After this event in August 1966 the governmental regulation on annual monitoring of high mountain lakes has been issued for the purpose of flood and debris flow prevention in Kyrgyzstan. Until that period investigations of lakes were episodic in terms of projects on debris flow hazard assessment. So far, a large volume of information has accumulated over this period, which formed the basis for the creation of hazardous lake inventory dataset. The first hazardous lake inventory in Kyrgyzstan, along with improved hazardous lake classification was developed in 1988 by [20]. 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. The database of potential hazardous lakes now contains 370 lakes divided into different categories of hazard [26]. The catalogue is dynamic and needs to be constantly updated. The main purpose of the tool for monitoring breakthrough lakes is to create a semi-automatic system to help specialists to carry out remote monitoring.

2. Methods

The principal objective of the automatic monitoring system is to collate and examine data obtained from a multitude of sources, including remote sensing data, historical data from archive reports, and field data. The processing of this information enables the formulation of recommendations for specialists with a view to enhancing the quality of the forecast material. In this study, we employed the genetic classification of lake types according to the lake dam material, which has been accepted in the Kyrgyz Republic and is presented in the 2020 publication by Erokhin and Zaginaev. Additionally, the catalogue of potential hazardous lakes was employed as an input to the system [26]. Prior to the implementation of the monitoring system, the entire process was conducted manually, beginning with the preparation and analysis of satellite images, the preparation of time-lapse, and concluding with the preparation of lake passports and lake survey reports.

Figure 1 shows the full algorithm of actions in the newly implemented system, including the creation of a lake passport based on the archival information contained in the lake catalogue, setting the parameters of the monitoring system and conducting field studies to confirm the recommendations of the system. Following a comprehensive evaluation of the potential for outburst hazards in semi-automatic mode, the hazard outburst categories for all 370 lakes have been updated and categorized as follows: very high, high, medium and low. The main criteria listed in the Table 1 [20]. In accordance with the recommendations of the system, the lakes are transferred from one category to another by a specialist followed the main criteria.

The NDWI index, which has been demonstrated to be effective in identifying high-altitude outburst lakes [27], was employed to ascertain changes in the extent of the lakes. The index has been tested using JavaScript to preprocess the Landsat OLI and Sentinel-2 MSI images based on the Google Earth Engine (GEE) platform, with the objective of tracking the dynamics of the area of potential hazardous lakes [28] with underground limited drainage. Shapefiles were constructed for the detected water bodies and then uploaded to GIS for analysis. For all lake types, an optimal threshold for the NDWI index of 0.2 was selected, with the aim of removing unnecessary noise.

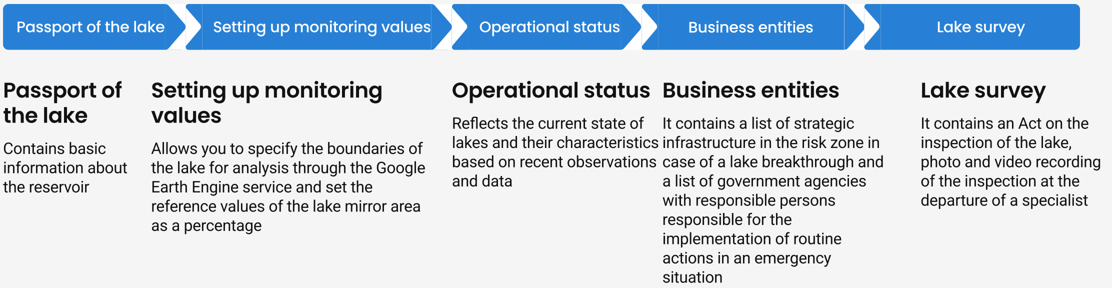

Figure 1: The recommended sequence of actions for monitoring potentially hazardous lake

Table 1: Criteria of hazard classification (Continue next page)

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	Very High / High
		Lake level is stable or gradually increasing. Outburst events in the past	Moderate / low
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	Very High
		Direct contact with glacier Underground Signs of dam subsidence along the underground channels Gullies and piping observed at the dam footslope Amplitude of lake water level fluctuation up to several meters; Gradual lake filling (1-3 years);	High
		Underground/combined outflow Signs of dam subsidence along the underground channels Gullies and piping observed at the dam footslope Amplitude of lake water level fluctuation is insignificant; stable regime of water inflow and outflow Gradual lake filling/lake level is stable;	Moderate
		Underground/surface (stable overflow) /combined outflow (stable) Gradual water level decrease	low
	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);	Very High
		Underground outflow Signs of dam subsidence in individual parts of lake basin banks Gradual lake filling	High
		Underground outflow Insignificant lake filling	Moderate
		Lake level is stable or decreasing	low
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	Very High
		Direct contact with glacier Underground Signs of dam subsidence along the underground channels Gullies and piping observed at the dam footslope Amplitude of lake water level fluctuation up to several meters; Gradual lake filling (1-3 years)	High

Table 1: Criteria of hazard classification (Continue from previous page)

Genetic class of lake	Subclass	Outburst susceptibility criteria	Hazard category
Bedrock-and moraine-dammed	-//-	Underground/combined outflow Signs of dam subsidence along the underground channels Gullies and piping observed at the dam footslope Amplitude of lake water level fluctuation is insignificant; stable regime of water inflow and outflow Gradual lake filling/lake level is stable	Moderate
		Underground/surface (in case of stable overflow) /combined outflow (stable) Gradual water level decrease	Low
Landslide-dammed	Rockslide-dammed	Underground outflow Gullies and piping observed on the downstream dam face. Amplitude of lake water level fluctuation up to several meters. Rapid lake filling	Very High
		Underground outflow Gullieson the downstream dam face Graduallakefilling	High
		Underground outflow/stable surface outflow Gullieson the downstream dam face Graduallakefilling Insignificant amplitude of lake water level fluctuation Stable regime of water inflow and outflow	Moderate
		Underground outflow Gradual water level decrease	Low
	Debris-flow-dammed lake	Absence of water outflow Rapid water level rise/possible water overflow	Very High
		Underground outflow Gradual water level increase	High
		Underground outflow/stable surface outflow Insignificant amplitude of lake water level fluctuation Stable regime of water inflow and outflow Underground outflow Gradual water level decrease	Moderate
	Landslide-dammed lake	Absence of water outflow Rapid water level rise/possible water overflow	Very High
		Underground outflow Gradual water level increase	High
		Underground outflow/stable surface outflow Stable regime of water inflow and outflow	Moderate
		Underground outflow Gradual water level decrease	Low

Additionally, data from available services and datasets, including ERA5, Open Weather, MODIS, CHIRPS 2.0, and GSmap, are downloaded via API for each lake. These data encompass atmospheric air temperature and precipitation, with the exception of the paid data from service “Windy”. The following services are responsible for the collection of short-term meteorological records pertaining to the state of the atmosphere in a given location at a specified point in time. In order to guarantee the stability, accuracy and reliability of temperature measurements and other weather data, a 'temperature buffer' is installed within the system with a radius of 10 km from the centre of the observation object. The case of Zyndan-West Lake, which experienced an outburst on 21 August 2024, illustrates the capacity of the system to assist specialists in monitoring lakes with a high risk of rupture. The most recent catastrophic outburst of this lake occurred on 24 July 2008 [29], yet following the outburst in 2008, the lake failed to refill, leaving the depression empty. Based on the analysis of past outbursts and the dynamics of lake filling, the system recommended that the category of outburst hazard should be upgraded and the category should be changed from medium to high. Further fieldwork was conducted on the lake to establish the flow channels and possible breakthrough mechanisms.

3. Study Site

Kyrgyzstan is a landlocked country in Central Asia, surrounded by the Tian Shan and Pamir Mountain ranges. Kyrgyzstan is greatly influenced by the orographic structure and topography, climatic conditions and the presence of glaciers [36]. The average altitude of the territory is 2,750 meters above sea level, the maximum is 7,439 meters and the minimum is 401 meters. More than 94 per cent of the territory of the Republic lies above 1000 m above sea level. It is of great importance to note the existence of extensive intermountain basins and valleys (Talas, Chui, Issyk-Kul, Naryn, Alai and others) located at an altitude of 500 to 3800 m in the Tien Shan region. The most developed plains are foothill, low-mountain, mid-mountain and inter-mountain depressions. The entire range of natural zones characteristic of the northern hemisphere, with the exception of tropical zones, can be found on the territory of the Republic. The climate is characterized by extremely continental. Within the territory of the Kyrgyz Republic the identified lakes are distributed in the following way: 166 lakes (45%) in Issyk-Kul region; 77 lakes (21%) in Chui region; 63 lakes (17%) in Osh and Batken regions; 26 lakes (7%) in Jalal-Abad region; 21 lakes (6%) in Talas region; 17 lakes (4%) in Naryn region. Among the types of lakes formed by natural processes, lakes with dams formed from landslides, glacial ice, and neoglacial moraines present the greatest threat to people and property [22]. In this study we used accepted in the Kyrgyz Republic genetic classification of lake types according to the lake dam material [20]. The mountain lakes in the territory of Kyrgyzstan can be classified into several types and subtypes and the criterion for such classification includes their genesis and related morphological features: ice-dammed; ice cored moraine-dammed; ice free moraine-dammed; bedrock and moraine-dammed; landslide-dammed. Figure 2 illustrates the distribution of eruptive lakes across the territory of the Kyrgyz Republic. Based on this distribution, it can be inferred that the primary concentration zones of breakthrough lakes are confined to the Teskey Ala-Too, Kyrgyz and Kungey Ala-Too ridges, which are part of the Tien-Shan Mountain system.

4. Results

Based on the survey of existing monitoring approaches of potential hazardous lakes, it was found that there is no systematization of the monitoring process from remote sensing data storage to field measurement data. Figure 3 shows the proposed and implemented integrated system of monitoring lake dynamics based on the IT infrastructure of the Department of Monitoring and Forecasting of Emergency Situations under the Ministry of Emergency Situations of the Kyrgyz Republic, including, in addition to the developed web application, a mobile module that allows uploading field survey data into the system and generating lake passports based on the analysis of remote sensing data within the system.

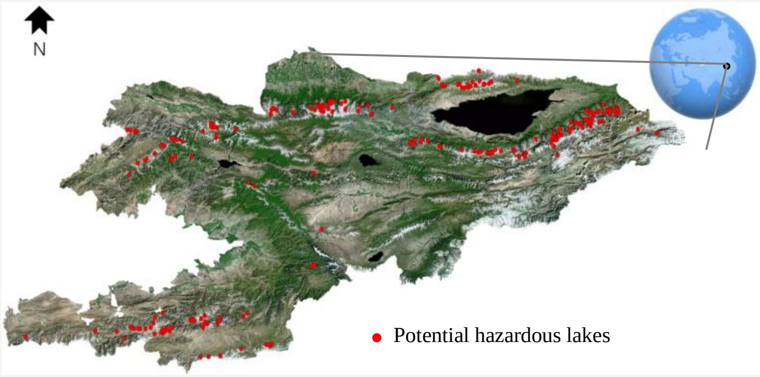

Figure 2: Distribution of potential hazardous lakes on Kyrgyz territory

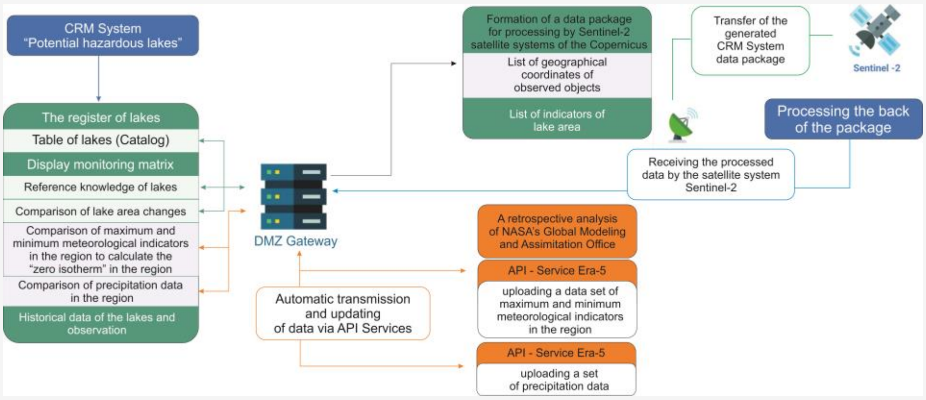

Figure 3: Process scheme for lake mirror area and boundary change algorithms

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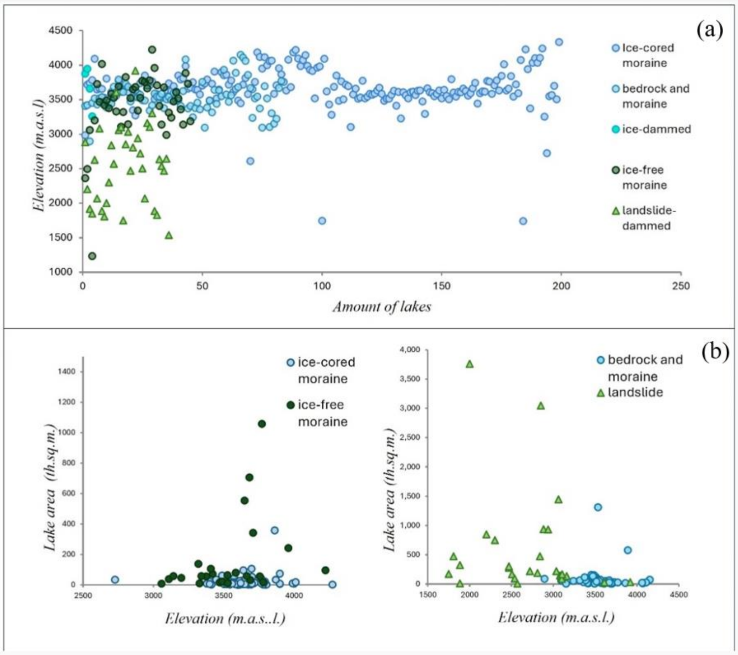

Figure 4: (a) Elevational distribution of lakes (b) Distribution of lakes by area and elevation

Table 2: Topographic and morphometric characteristics of hazardous lakes in Kyrgyzstan

Genetic type of lakes	Elevation ranges (m)		S (m²) Min. (×10³)	S (m²) Max. (×10⁶)
Ice-dammed	Min.	3,266	4-5	5
	Max.	3,945		
	Mean	3,689		
Ice cored moraine-dammed	Min.	2,726	4-5	4
	Max.	4,335		
	Mean	3,665		
Ice free moraine-dammed	Min.	1,235	8-10	1
	Max.	4,224		
	Mean	3,413		
Bedrock and moraine-dammed	Min.	2,895	4-5	1
	Max.	4,150		
	Mean	3,534		
Landslide-dammed	Min.	1,536	5-6	5
	Max.	3,918		
	Mean	2,548		

A total of 370 susceptible to outburst lakes in Kyrgyzstan were identified inventoried and classified into 4 classes: ice-dammed, moraine-dammed, bedrock- and moraine- dammed, landslide-dammed lakes. The analysis led to the identification of areas for all types of lakes included in the catalogue of potential hazardous lakes, which were subsequently updated with the new data. The results of the analysis are presented in Table 2 and Figure 4. Given that the lake area is a dynamic parameter, the system is designed to automatically adjust this parameter in line with seasonal changes. All lakes in the catalog located at the elevational zone between 1200 m.a.s.l. and 4300 m.a.s.l. Elevations of landslide-dammed lakes range from 1536 to 3918; ice-cored moraine-dammed lakes from 2726 to 4335; ice-free moraine-dammed lakes from 1235 to 4224; ice-dammed lakes from 3266 to 3945; bedrock and moraine-dammed lakes from 2895 to 4150.

The majority of the detected studied lakes is distributed in the range between 3300 and 4300 m a.s.l. moraine-dammed lakes and refers to moraine-dammed and bedrock-and-moraine dammed lakes. Most of the landslide-dammed lakes are found at a lower elevation zone (3200-1700 m.a.s.l).

All these lakes were described by a number of quantitative and qualitative characteristics and have different levels of outburst susceptibility [20]. A total of 197 lakes were qualitatively estimated in terms of their surface area, which ranges from thousands to millions of square meters.

4.1 Data on Past Lake Outbursts

The system incorporates data on historical instances of lake outbursts that have caused damage to infrastructure and affected the population. As illustrated in Table 3, in numerous valleys, debris flows resulting from breakthroughs have occurred on multiple occasions.

Table 3: Registered GLOF events in Kyrgyz Republic (continue next page)

No.	Name_of_lake	River_valley	Date of outburst	Discharge (m^3/s)	Type_of_lake	Location
1	Teketor (CH-12)	Tuyuk-Issyk-Ata	16/8/1953 -/08/1978	40-50 30	ice-cored dammed	North slope of Kyrgyz Range
2	Takyrtor (CH-55)	Noorus	4/06/1992 4/06/2009	NA. 25	ice-cored dammed	
3	Teztor (CH-8)	Ala-Archa	22/06/1953 -/06/1988 -/07/2004 31/07/2012	50 NA. 6-8 10-15	ice-cored dammed	
4	Top-Karagay (CH-10)	Ala-Archa	1974 1993	10-15 10-15	ice-cored dammed	
5	Aksay (CH-40)	Ala-Archa	50/07/1960 26/07/1961 21/08/1965 18/06/1968 24/07/1969 18/07/1970 04/08/1975 18/07/1980	NA.	englacial tank	
6	Isha (CH-3)	Aksuu	-/06.1968	40		
7	Keidy-Kuchkach (CH-4)	Aksuu	-/07/1980 12/08/1983	40 40-60	ice-cored dammed	
8	At-Djailoo (CH-13)	Kegety	13/07/1968	NA.	ice-cored dammed	
9	Djerdy-Kaindy (CH-26)		1995	NA.	ice-cored dammed	
10	Akpay	Sokuluk	02/08/2020	40-60	ice-cored dammed	
11	Djalpaktor (T-2)	Chyrkanak Talas	20/06/1969 14/07/1976 -/07/1991 -/07/1997	NA. NA. 20 10 NA.	ice-cored dammed	South slope of Kyrgyz Range
12	Kyzyl-Djar (I-72)	Chon-Aksuu	15/07/1958	50	ice-cored dammed	Issyk-Kul lake Bassin
13	Chon-Kyzylsuu (I-29)	Chon-Kyzylsuu	5/06/1959 -/10/1966 11/07/1968	NA. NA. 50	ice-cored dammed	
14	Tamga (I-6)		12/08/1964	30	ice-cored dammed	
15	Tosor (I-176)	Tosor	9/07/1995	60	ice-cored dammed	
16	Angysay	Ton	14/06/1974 17/06/1975 25/06/1980	NA.	englacial tank	
17	Choktal-1 (I-1)		27/09/1978	NA.	ice-cored dammed	
18	Choktal-2 (I-2)		-/09/1999y	20	ice-cored dammed	
19	Chonkoisuu (I-12)		14/06/1994	20	ice-cored dammed	
20	Suyuk-Tor (I-10)	Djerui	2005	NA.	ice-cored dammed	

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Table 3: Registered GLOF events in Kyrgyz Republic (Continue from previous page)

No.	Name_of_lake	River_valley	Date of outburst	Discharge (m^3/s)	Type_of_lake	Location
21	Koltor (I-35)	Ton	-/07/2003	NA.	ice-cored dammed	Issyk-Kul lake Bassin
22	Kurumdy (I-172)		-/07/2015	NA.	ice-cored dammed	
23	Chetyndy (I-181)	Djerui	15/08/2013	NA.	ice-cored dammed	
24	Zyndan (I-167)		-/07/2008 21/08/2024	NA.	ice-cored dammed	
25	Buzulgansuu (N-14)		-/07/1987 2006	NA.	Glacial-lake	Naryn
26	Shahimardan (O-20)		-/07/1998	NA.	ice-cored dammed	South of Kyrgyzstan
27	Tegermach-south (O-15)		-/07/1999	NA.		
28	Tegermach-north (O-16)		-/07/1977	NA.		
29	Jashylkul		18/06/1966	NA.	Landslide dammed	

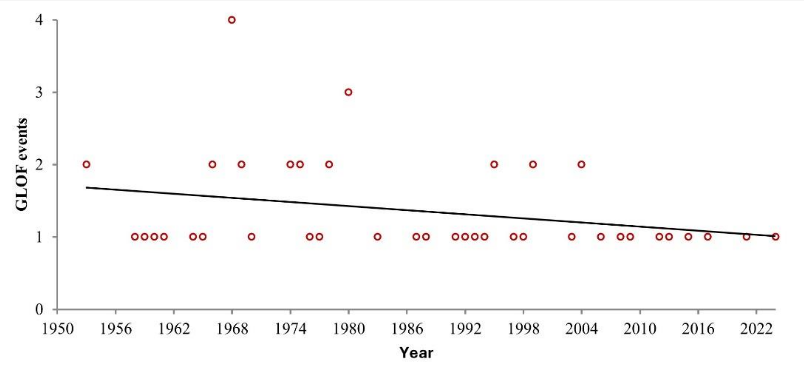

Figure 5: Distribution of GLOF events

The greatest activity associated with lake outburst occurred between 1960 and 1980 (Figure 5), mainly associated with glacier activity and outburst from Aksai Glacier [4] and [5]. The average frequency of outburst glaciers over the last 20 years is 1 outburst glacier every three years. A series of criteria have been devised for all types of lakes, as illustrated in Table 4, which permit the classification of lakes according to hazard categories, the analysis of meteorological conditions, and the grouping of lakes into categories, thereby facilitating the transfer of a lake from one category of outburst hazard to another.

4.2 A Forecast of the Lake Zyndan Outburst in 2024

Zyndan-West Lake (I-167) was upgraded to a high outburst hazard based on system results and recommendations based on changes in lake area parameters, historical outbursts, and field survey data. Outburst floods from glacial lakes can cause damage up to several hundreds of kilometers downstream. Figure 6(a) shows a comparison of the lake area before and after the outburst, with blue showing the lake area on 9 August 2024 and red showing the lake area after the outburst in the 28 August 2024 image.

Due to cloudiness and impossibility to estimate whether the lake ruptured with the whole volume or a partial drainage, Sentinel-1 images on the GEE platform side were uploaded to the system and analysed, which allowed to estimate that the lake ruptured in the same scenario as in 2008 and with the same volume. In accordance with the rapid filling of the lake, recommendations were made in July 2024 to upgrade the lake to high hazard. Following an aerial UAV survey, the decision was taken to upgrade the lake to very high rupture hazard, a decision that is consistent with the data shown in Table 4.

Table 4: Characteristics and criteria of lake outburst hazards

The main feature of a group of lakes	Characteristics of each lake group	Outburst hazard criteria for each group of lakes	Level of outburst
Lakes with almost annual draining	Glacial lakes with interglacial runoff channels	Filling of lakes with limited drainage	Very High
Lakes with a risk of outbursting after partial or total drainage	Moraine-glacial lakes of intramoraine depressions. Filling during 2-3 months and obligatory outburst is possible	Filling of lakes. Development of underground flow channels.	Very High
Lakes without outbursts, during the last 5-10 years retain signs of high outburst risk	Moraine-glacial lakes of intramoraine depressions with impeded groundwater flow. The lake basin expands behind the retreating glacier.	Development of underground channels. Filling of the lake. Lowering the cofferdams.	Very High / High
Lakes with no outbursts but with indications of high hazard of outburst in the last 1-3 years	Moraine-glacial lakes of intramoraine depressions with unstable groundwater flow, with large volume fluctuations.	Filling of lakes. Development of underground flow channels.	Very High / High
Lakes which, even after partial drainage, retain a high risk of outburst	Moraine-glacial lakes with permanent filling of lakes	Development of underground channels. Filling of the lake. Lowering the cofferdams	High
Lakes without a outbursts, during the last 3-5 or more years retain signs of outburst development	Moraine-glacial lakes of intramoraine depressions with stable groundwater drainage	Filling of lakes. Development of underground flow channels.	Moderate
The lakes, after partial or complete drainage, have passed into a stage of quietly stable development, with an unusual possibility of a new outburst	The lakes are moraine-glacial intramoraine depressions and thermokarst lakes, as well as rockglacier dammed lakes. It is possible to restore their outburst capacity only under significant changes in natural conditions	Extreme event. Filling of lakes.	Low
Lakes without outburst events, during the last 3-5 and more years retain the signs of stable non-hazardous development	Moraine-glacial lakes of intramoraine depressions. Constantly retain some volume of water in their baths even in winter.	Extreme event. Filling of lakes.	Low

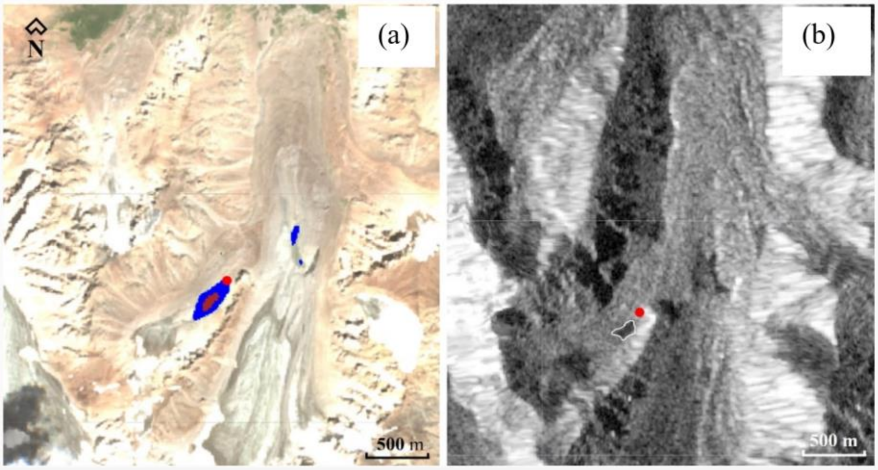

Figure 6: (a) Zyndan-West Lake on Sentinel-2 image,
(b) Verification of the breakthrough on Sentinel-1 image

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Upon analysis of the satellite imagery within the system four days prior to the breach, a decline in the lake's elevation was observed. The lake's surface area decreased from 410,000 m² to 350,000 m², indicating the emergence of subterranean flow channels and the commencement of drainage. Prior to this, the lake exhibited an increase in volume. Based on previous bathymetric measurements, the volume of the lake at maximum capacity was approximately 400×10^3 m³. In light of the opening of flow channels, it was predicted that the lake would burst within the next 10 days. Consequently, equipment was prepared and works on deepening the riverbed was initiated. On the day of the bursting, over 300 people were evacuated from Turasu village to a safe location. Following the analysis of satellite images and the determination that the lake had burst almost completely (two days later), the decision was made to return people to Turasu village.

5. Conclusion

The hazard of Glacial Lake Outburst Floods (GLOFs) in the Kyrgyz Mountains is a significant concern due to the region's topography, climate, and the presence of numerous glacier-fed lakes. GLOFs are potentially devastating events that occur when glacial lakes, often dammed by ice or moraine, suddenly release large volumes of water, debris, and sediment, leading to downstream flooding. The Kyrgyz Mountains, like many other mountain ranges around the world, have experienced significant glacier retreat as a result of climate change. This retreat can lead to the exposure of new lakes or the enlargement of existing ones, increasing the potential for glacial lake outburst floods (GLOFs). Additionally, Kyrgyzstan is located in a seismically active zone, which can trigger landslides or destabilize glacial dams, leading to GLOFs. Earthquakes can also dislodge ice and moraine material, causing downstream flooding.

Recent climate studies in the region indicate significant changes in the cryosphere that may also affect the formation and outburst of high mountain lakes in the region, but the lack of climate data for the high mountain zones of Kyrgyzstan indicates the need for more detailed studies in the future. The categorisation of lakes and the level of hazard outburst are also contingent upon local climatic factors and are directly related to changes occurring in the cryosphere. For example, following the retreat of glaciers, the number of lakes increases, resulting in the filling and GLOF from moraine-glacial type, which had not undergone recent filling in recent years (Akpay Lake, Zyndan-West Lake). In previous years, the categories had to be changed manually at the end of the last field season. Of all the lakes in the catalogue, only 10-20 were subjected to field studies.

The system allows for the prioritization of the field season and the orientation of field groups throughout the season. As evidenced by the successful forecast of the Zyndan-West Lake outburst, this approach to forecasting is justified and allows for a more rational approach to the issues of protection of population and territories from outbursts of high-mountain lakes. Since the vast majority of the Kyrgyz Republic is situated within an area of high seismic activity [30], the system also encompasses the notification and visualization of earthquake epicenters. Given the dearth of research in this field, this factor is taken into account and information is accumulated in the system. However, the actual impact of earthquakes on the stability of high-mountain lake dams is extremely challenging to assess.

6. Discussion

The semi-automatic monitoring system for potential hazardous lakes enables MES KR specialists to monitor and adjust the extent of lake outbursts during the season, thereby enhancing the quality of forecast material and increasing the resilience of local communities to the risks associated with high-mountain lake outbursts. Examples of successful forecasting of the outburst hazard period include the forecast of the outburst of Teztor Lake on 31 July 2012 [31], when a warning of a possible outburst in the next two decades was given based on visual survey data and using stationary monitoring data two weeks before the lake outburst. The rapid development in Geographic information systems and Remote sensing cause these technologies have become the most powerful tools for spatial analysis and applications in the wide range of fields including natural hazard mapping and risk assessment [35]. In a period of approximately two weeks, the scenario of a potential GLOF was also described, and the maximum debris flow rate was calculated based on the morphology of the valley and the presence of a powerful debris flow center in the valley. The second example is the outburst of non-stationary moraine-glacial lake Akpay on 2 August 2021. This was detected on the basis of data from the “Landviewer” service, which has limitations in the free version. An accumulation of water was observed in the depression located in the upper reaches of the Akpay valley, the left tributary of the Sokuluk River. Following the issuance of a notification to the relevant state authorities, a task force was constituted.

Subsequent to an investigation, evidence of subsidence of the lake dam was identified, leading to the issuance of a cautionary statement regarding the potential for a breach. In order to guarantee the safety of the local population, the decision was taken to evacuate those engaged in pastoral activities situated upstream of the Sokuluk River. Additionally, warning notices were displayed for tourists and the local population, alerting them to the prevailing threat. One of the unique features of this system is its ability to conduct a retrospective analysis of data, especially on such critical parameters as changes in the mirror of the lake area and temperature indicators. This analysis allows you not only to track the current state of sites, but also to analyze historical data to identify trends, predict potential risks and develop strategies to minimize them. Thus, the system provides an integrated approach to security monitoring, combining immediate actions to prevent immediate threats and long-term planning based on the analysis of historical data.

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