

Review

Lake Sarez and the Usoi Dam in Tajikistan: Hazard Assessment, Stability and Risk Management Perspectives

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Abstract

Lake Sarez in Tajikistan, formed by a major earthquake-induced landslide in 1911, is located in the highly seismically active Pamir–Hindu Kush region. The lake is impounded by the Usoi Dam, one of the largest natural landslide dams in the world, which has raised concerns regarding its long-term stability and associated downstream flood hazards. Due to its geomorphological setting and potential exposure to multiple triggering mechanisms, including seismic activity and landslides, Lake Sarez is widely considered a high-consequence hazard system. Although the dam has remained stable for over a century and is currently monitored using modern geodetic and satellite-based technologies, uncertainties remain regarding its internal structure and response to extreme external forcing. While existing early warning systems enhance preparedness in downstream communities, effective long-term risk reduction requires continued monitoring, improved hazard modeling, and strengthened regional cooperation. This review synthesizes existing studies on the geological setting, hazard potential, stability assessments, and disaster risk management strategies related to Lake Sarez. It highlights the importance of integrated multi-hazard analysis and precautionary risk governance in managing low-probability but high-impact natural dam failure scenarios.

Keywords: Sarez Lake; Usoi Dam; Central Asia; Tajikistan; Pamir Mountains

1. Introduction

In 1911, a powerful Mw 7.7 earthquake in remote Gorno-Badakhshan Autonomous Region of Tajikistan triggered a massive landslide that blocked the Bartang River. The resulting natural dam, known as the Usoi Dam, is one of the highest in the world, rising 550 m above the valley floor [1]. This natural barrier created Lake Sarez, which spans over 60 km in length, exceeds 500 m in depth, and holds approximately 17 km³ of water [2]. Located at an elevation of 3200 m and surrounded by peaks exceeding 6000 m (see Table 1), in this remote and isolated region, the dam holds a water volume seven times larger than its rock barrier, posing catastrophic risks if breached [3].

Despite its impressive size and long-term persistence, the stability of the Usoi Dam remains a subject of scientific debate. Some studies suggest that the system may be vulnerable under extreme conditions, particularly seismic events or landslide-induced wave impacts, which could potentially lead to dam overtopping or structural weakening. Such scenarios highlight the potential for high-magnitude downstream flooding, making Lake Sarez one of the most significant natural dam systems in terms of potential consequences [4].



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Table 1. Physical characteristics of Lake Sarez.

Formation year	1911
Lake length	~60 km
Maximum depth	>500 m
Water volume	~17 km ³
Elevation	~3264 m
Dam height (Usoi Dam)	~560 m
Average width	1.44 km
Surface area	84.37 km ²
Catchment area	19,564 km ²

Note: Compiled using data from [1–5].

The region surrounding Lake Sarez is highly susceptible to natural hazards, including earthquakes, landslides, and floods. Its location within the seismically active Pamir Mountains means that tectonic activity remains a key factor influencing long-term stability [6].

In addition, climate change is accelerating glacier retreat and reshaping hydrological regimes across the Pamir Mountains, increasing environmental instability in high-altitude regions [5,7]. Rising temperatures and changing precipitation patterns are expected to intensify glacier melt, promote the formation and expansion of glacial lakes, and increase the likelihood of glacial lake outburst floods (GLOFs) [8,9]. These processes may increase inflow variability and hydrostatic pressure on the Usoi Dam, introducing additional uncertainty for future hazard assessments [10].

In contrast, other researchers argue that the dam has remained stable for more than a century due to its massive rock structure and geomorphological setting [11]; however, its long-term behavior under combined seismic and climatic stress is still not fully understood.

Recent studies and monitoring initiatives using GPS, satellite remote sensing, and BeiDou (BDS) systems have been applied to detect deformation and improve hazard assessment in the region [12]. However, uncertainties remain regarding the interpretation of long-term stability trends, particularly under future extreme events.

Effective risk mitigation therefore requires continuous monitoring, strengthened early warning systems, improved seismic and geological assessments, and enhanced community preparedness. Furthermore, transboundary cooperation among downstream countries is essential for coordinated disaster risk management.

This review paper synthesizes existing scientific knowledge on Lake Sarez and the Usoi Dam, focusing on hazard mechanisms, stability assessments, and risk management strategies. It also identifies key gaps in multi-hazard integration, monitoring interpretation, and regional disaster preparedness.

Finally, despite significant scientific attention, major gaps remain in understanding long-term dam stability under combined seismic and climate influences, as well as in translating scientific knowledge into effective risk reduction strategies across the region.

2. Methodology

This study employed a narrative literature review approach to synthesize existing knowledge on the geological, hydrological, climatic, and disaster-risk aspects of Lake Sarez and the Usoi Dam. Relevant literature was identified through searches of Google Scholar, Scopus, Web of Science, and institutional publications from international organizations, including the United Nations, the World Bank, the Asian Development Bank, and other relevant agencies.

Search terms included “Lake Sarez”, “Usoi Dam”, “Sarez earthquake”, “landslide dam”, “Pamir Mountains”, “natural dam stability”, “earthquake hazards in Tajikistan”, “Lake Sarez monitoring”, and “climate change impacts in the Pamirs”. Publications from 1911 to 2025 were considered, with emphasis placed on peer-reviewed journal articles, technical reports, and authoritative institutional assessments directly related to Lake Sarez and associated hazards.

Sources were selected based on their relevance to dam stability, seismic hazards, landslide processes, monitoring systems, flood risk assessment, and regional disaster management. Duplicate sources and publications lacking direct relevance to the study objectives were excluded. The collected literature was subsequently analyzed and synthesized to identify major hazard scenarios, monitoring developments, risk management approaches, and areas of scientific agreement and uncertainty.

3. Geological and Seismic Setting of Lake Sarez

The Lake Sarez system is located within the highly active tectonic environment of the Pamir Mountains in Central Asia, where the Indian and Eurasian plates interact [13]. This region is characterized by intense crustal deformation, frequent seismic activity, and complex fault systems, including the Sarez-Karakul fault zone. These tectonic conditions have historically generated large earthquakes capable of triggering landslides and slope failures [6].

The formation of Lake Sarez in 1911 was directly caused by a catastrophic earthquake that induced a massive rock avalanche, which blocked the Bartang River and created the Usoi Dam [14]. The resulting natural dam consists of unconsolidated rock debris, which, despite its long-term stability, remains geotechnically heterogeneous and highly sensitive to external forcing, such as seismic shaking and hydrological pressure [15].

The surrounding topography is extremely steep, with valley walls rising sharply to elevations exceeding 6000 m [16]. This geomorphological setting increases susceptibility to rockfalls, landslides, and mass wasting processes that may directly impact the lake system. In addition, the high-altitude environment is influenced by active glacial processes, which further shape slope stability and sediment dynamics.

Seismicity in the Pamir region remains significant, with historical and recent earthquakes demonstrating the ongoing tectonic activity. Events such as the 2015 Mw 7.2 earthquake highlight the potential for reactivation of fault systems and secondary hazard generation in the region [16,17]. These seismic conditions represent a key controlling factor in assessing the long-term stability of the Usoi Dam and the overall hazard potential of Lake Sarez.

4. Hazard Perspectives

Lake Sarez is in a seismically active area, with large earthquakes occurring every 100 to 2000 years. Such seismic events have the potential to destabilize the Usoi Dam either through direct structural damage or indirectly by triggering slope failures and increasing seepage through the dam body. Given the unconsolidated nature of the landslide debris, the dam remains highly sensitive to strong ground shaking and hydrological pressure variations [17].

Tectonic deformation in the Pamir region contributes to ongoing seismic hazard, particularly along the Sarez-Karakul fault system. Studies indicate that fault reactivation and complex rupture geometries increase the likelihood of future seismic events in the region [18,19]. Satellite-based investigations further confirm active surface deformation and repeated seismic ruptures, highlighting persistent tectonic stress accumulation [6].

Historical and recent earthquakes, including the 1911 Mw ~7.3 event and the 2015 Mw 7.2 Sarez earthquake, demonstrate the long-term seismic activity of the region and indicate ongoing strain accumulation along regional fault systems [20]. Some studies also suggest increased seismicity following major regional events, further emphasizing the dynamic tectonic environment [21].

Additional concerns relate to potential mass movements from the right bank slopes (see Figure 1), which could generate displacement waves capable of overtopping the dam [22]. Such scenarios have been widely studied because of their potential to trigger severe downstream flooding affecting multiple countries in Central Asia [23].

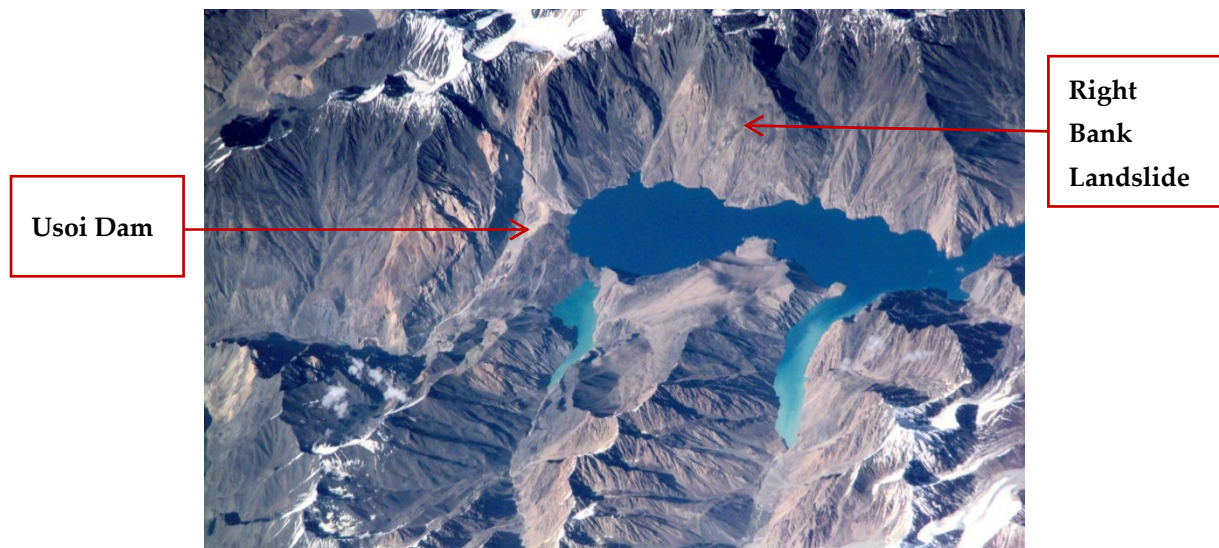


Figure 1. Sarez Lake. Source: NASA [24].

Hydromechanical processes also contribute to hazard potential. While complete dam collapse is considered unlikely under normal conditions, variations in seepage patterns and slope instability triggered by seismic shaking or landslide-generated waves may still compromise dam stability [15].

Advanced monitoring systems, including GPS and BeiDou (BDS) technologies, have been deployed to observe deformation processes at the dam. Although recent observations indicate overall stability, significant displacement was recorded following the 2023 Mw 7.2 earthquake, highlighting the sensitivity of the system to seismic forcing [16].

The study by Nardini et al. [25] employed two advanced methods—InSAR using the SqueeSAR approach and optical imagery with COSI-Corr software—to analyze two large landslides around Lake Sarez in Tajikistan. The research highlights that the collapse of these landslides could generate an unusual wave, potentially overtopping the dam. Such an event poses a severe threat to the safety of communities living near the lake and along the downstream river [25].

Yu et al. [13] used SBAS-InSAR deformation monitoring and susceptibility modeling to identify ongoing slope movements around Lake Sarez, with maximum displacement rates reaching 280–480 mm per year in some areas. Their findings indicate that continued deformation may threaten dam shoulder stability, highlighting the need for continuous monitoring and early warning systems.

Landslide dam failure mechanisms are often associated with earthquake-triggered slope collapse or extreme rainfall events, and modeling studies emphasize the importance of such processes in disaster risk evaluation [1,26,27]. Historical analogues, including the Vajont disaster, demonstrate the destructive potential of overtopping waves generated by landslides [28]. Long-term studies of the Vajont landslide highlight the complexity

and uncertainty of landslide-dammed systems, including evolving interpretations of slope stability and the influence of hydrometeorological factors such as rainfall and reservoir water level changes [29].

At a broader scale, historical natural dam failures exhibit a consistent pattern in which multiple triggering factors interact to produce rapid collapse. Earthquake shaking, intense rainfall, and progressive slope weakening commonly initiate dam instability, which may evolve into overtopping, breaching, or internal erosion, ultimately resulting in sudden downstream flooding. Representative cases of historical landslide-dammed systems—including the Dadu River damming event (1786, China), Diexi (1933, China), Tangjiashan (2008, China), Attabad Lake (2010, Pakistan), and the Gros Ventre landslide (1927, USA), as shown in Table 2, demonstrate substantial variability in both triggering conditions and failure mechanisms.

Table 2. Summary of selected historical cases of natural dam failures, illustrating the variability of triggering mechanisms and associated impacts.

Name	Location	Year	Cause	Fatalities
Val Pola	Italy	1987	Rainfall	27
Dadu River	China	1786	Earthquake	~100,000
Poerua River	New Zealand	1999	Landslide	0
Diexi	China	1933	Landslide	150
Yigong River	China	2000	Landslide	100
Tangjiashan	China	2008	Earthquake	0
Attabad Lake	Pakistan	2010	Landslide	20
Sunkoshi	Nepal	2014	Rainfall	0
Gros Ventre	USA	1927	Hydro-seismic	6

Note: compiled using data from [30–38].

The Sarez Lake rockslide dam poses a significant risk to nearby communities and infrastructure. In a regional Central Asian context, rockslide-dammed lakes in the region have triggered catastrophic outburst floods, like the 1841 Indus rockslide flood. Therefore, while Sarez Lake is an extraordinary geological formation, it remains a serious hazard that demands ongoing monitoring and effective risk management strategies [39]. Havenith [40] highlights the danger of a potential Sarez Lake dam breach by citing the 1992–1993 Belaldy rockslide case. This case demonstrated how the partial failure of a landslide dam can lead to devastating downstream impacts, highlighting the risks associated with the unstable rubble dam of Sarez Lake [40].

Climate change may further increase hazard potential in the Pamir Mountains. Recent research indicates that accelerated glacier retreat, changing precipitation patterns, and increasing hydrological variability are reshaping mountain environments across Tajikistan [41]. In addition, climate-related factors such as rainfall, temperature, and water level variations may influence slope deformation [42].

Overall, hazard studies emphasize that Lake Sarez represents a high-consequence system where multiple triggering mechanisms—seismic activity, landslides, and hydroclimatic processes—may interact to produce extreme but low-frequency events.

5. Stability Perspectives

In contrast to hazard-oriented assessments, several studies suggest that the Usoi Dam has demonstrated long-term structural stability since its formation in 1911. This

interpretation is primarily based on the dam's large scale, rocky composition, and lack of evidence for progressive structural failure over more than a century.

Geotechnical analyses indicate that internal erosion and complete dam collapse under normal hydrological conditions are unlikely. The primary concern identified in several studies is not structural failure of the dam body itself, but potential overtopping caused by external triggers such as landslides or extreme inflow events. Even under such scenarios, catastrophic failure is considered unlikely due to the dam's coarse rock composition and high permeability resistance [11].

Geodetic and remote sensing studies provide additional evidence supporting relative long-term stability. GPS and satellite-based observations indicate that slope movements in the surrounding areas do not currently show signs of large-scale destabilization [43]. Although localized deformation exists, it does not suggest imminent structural collapse.

Hydrogeological investigations further suggest that seepage through the dam is slower than initially estimated. Tracer studies indicate limited internal erosion activity, which reduces the likelihood of rapid dam weakening or failure [28].

Nevertheless, uncertainties remain regarding the internal structure of the dam and its long-term mechanical behavior under combined seismic and hydrological stress. Some authors emphasize that while the system appears stable under current conditions, the lack of detailed subsurface data limits definitive conclusions regarding its ultimate stability [44].

Therefore, although available evidence supports the general stability of the Usoi Dam, the system remains uncertain under extreme loading conditions, particularly in the context of future seismic- and climate-driven changes.

6. Synthesis of Hazard and Stability Evidence

The scientific literature on Lake Sarez and the Usoi Dam presents two contrasting but complementary perspectives: one emphasizing the potential for extreme hazard events, and the other highlighting the long-term stability of the natural dam structure. Rather than being mutually exclusive, these perspectives reflect different aspects of the same geosystem operating under varying temporal and triggering conditions.

Hazard-oriented studies emphasize that Lake Sarez is located in a highly active tectonic region where large earthquakes, slope failures, and hydrological extremes may interact to produce low-frequency but high-magnitude events. The large volume of stored water, steep valley geometry, and proximity to active fault systems collectively support the possibility of extreme scenarios such as landslide-generated waves, dam overtopping, and downstream flooding across multiple countries [19,25]. From this perspective, the system is characterized by high exposure and high potential consequences.

In contrast, stability-focused studies highlight the long-term persistence of the Usoi Dam since its formation in 1911, despite repeated exposure to seismic events and climatic variability. Geotechnical and geodetic investigations indicate no clear evidence of progressive structural failure or large-scale deformation, suggesting that the dam has reached a relatively stable geomorphic configuration under current boundary conditions [11,28,43]. These findings indicate that catastrophic failure under normal hydrological conditions is not supported by current observational evidence.

The apparent contradiction between these two perspectives can be reconciled by distinguishing between structural stability and external triggering mechanisms. While the dam itself appears to exhibit long-term mechanical stability, it remains sensitive to external perturbations such as strong seismic shaking, landslide impacts, or extreme hydrological events. Therefore, the primary risk is not continuous structural degradation, but the possibility of rare triggering events that could initiate rapid failure processes.

This interpretation supports a risk framework in which Lake Sarez is classified as a low-probability, high-consequence hazard system. In such systems, the absence of observed failure over long timescales does not eliminate risk, but rather shifts attention toward understanding extreme event scenarios and their cascading impacts.

Furthermore, significant uncertainties remain in the characterization of the dam's internal structure, the magnitude–frequency relationship of regional earthquakes, and the dynamics of potential landslide-generated impulse waves. These uncertainties limit precise quantitative estimation of failure probability but do not eliminate the need for precautionary monitoring and preparedness.

Overall, the integrated evidence suggests that Lake Sarez should not be interpreted either as an imminent disaster or as a fully stable system. Instead, it represents a geologically stable but externally sensitive system where extreme events, although rare, could produce catastrophic downstream consequences. This duality underscores the importance of continuous monitoring, multi-hazard risk assessment, and transboundary disaster preparedness.

7. Disaster Management and Early Warning Systems

Recognizing the potential consequences of a catastrophic failure of the Usoi Dam, national authorities and international organizations have implemented a range of monitoring, early warning, and disaster risk reduction measures. These efforts aim to improve hazard detection, strengthen preparedness, and reduce the vulnerability of downstream communities.

A major milestone was the implementation of the Lake Sarez Risk Mitigation Project (LSRMP), supported by the World Bank and the United States Government. The project focused on establishing monitoring and early warning systems, strengthening institutional disaster management capacity, improving community preparedness, and evaluating long-term risk reduction options. Through the installation of communication infrastructure and warning mechanisms, the project significantly enhanced the ability of authorities and local communities to respond to potential emergencies [45].

Building upon these efforts, the Government of Tajikistan, with support from international partners, established an early warning system covering communities in the Bartang Valley and along the Panj River that could be affected by a potential dam failure. The system integrates satellite, VHF, and other communication networks linking key operational centers in the region, thereby improving the dissemination of emergency information and warning messages [46].

International support has continued through initiatives aimed at strengthening monitoring capabilities and risk assessment. The Asian Development Bank (ADB) has supported activities such as dam-break analysis, flood modeling, hazard mapping, disaster risk modeling, and capacity building, contributing to improved understanding of hazards associated with Lake Sarez [47].

Recent technological advances have further improved monitoring of the Usoi Dam. Since 2021, a joint Chinese–Tajik research initiative has employed the BeiDou (BDS) satellite navigation system, together with GPS technologies, to conduct high-precision measurements of dam deformation and lake-level fluctuations. These systems provide near-real-time observations and improve the detection of potential changes in dam behavior, particularly in response to seismic activity [12].

In addition, the National Disaster Risk Management Project launched in 2019 supported further assessments of the Lake Sarez monitoring network and identified opportunities for system modernization and expansion. Subsequent recommendations included

extending early warning coverage to additional vulnerable areas, including settlements near the Afghanistan border and parts of Khatlon Province in Tajikistan [46].

Despite substantial progress in monitoring and preparedness, several challenges remain. The remoteness of the region, harsh environmental conditions, limited infrastructure, and persistent uncertainty regarding extreme hazard scenarios continue to complicate effective disaster management. Consequently, continued investment in monitoring technologies, early warning systems, emergency planning, community preparedness, and regional cooperation remains essential for reducing disaster risk associated with Lake Sarez [47].

8. Future Risk and Sustainable Development

Several proposals have been advanced to utilize Lake Sarez as both a strategic water resource and a mechanism for reducing long-term hazard risks. These proposals seek to balance disaster risk reduction with regional water and energy needs.

Recent discussions between Tajikistan and Uzbekistan have explored the potential use of Lake Sarez's water as a source of freshwater for domestic consumption. During the 7th meeting of the Joint Working Group on the Comprehensive Use of Water Resources of Transboundary Rivers in Central Asia, held in Dushanbe in August 2024, both countries considered opportunities for future cooperation regarding the utilization of Sarez Lake water resources [17].

Beyond Central Asia, proposals have also been made to export water from Lake Sarez to water-scarce countries, including Iran, Jordan and the United Arab Emirates. While such initiatives could contribute to regional water security, their technical feasibility, environmental implications, economic costs, and potential effects on hazard management require further investigation [17].

The international significance of Lake Sarez has also been recognized at the highest political levels. In June 2017, United Nations Secretary-General António Guterres visited Lake Sarez, drawing attention to both its potential risks and its broader importance for sustainable development and regional cooperation [48].

Among suggested mitigation strategies, some studies, including Deng et al. [5], indicate the potential feasibility of constructing a hydropower facility that could contribute to gradual lake level regulation while generating renewable electricity.

However, the implementation of any large-scale development project at Lake Sarez must carefully consider geological, seismic, environmental, and social factors. As climate change intensifies water scarcity across Central Asia and neighboring regions [49], interest in utilizing Lake Sarez as a strategic freshwater resource may continue to grow. Nevertheless, sustainable management of the lake requires balancing development opportunities with hazard mitigation objectives, scientific uncertainty, and the need for effective regional cooperation.

Consequently, future strategies should prioritize comprehensive feasibility studies, transboundary coordination, environmental safeguards, and risk-informed planning to ensure that any utilization of Lake Sarez contributes to both regional development and long-term disaster risk reduction.

9. Conclusions and Recommendations

Lake Sarez presents both a natural marvel and a potential high-consequence hazard. While its formation reflects powerful geological processes, its location in a seismically active region, susceptibility to landslides, and the structural characteristics of the Usoi Dam pose significant risks to downstream communities. Therefore, effective and coordinated disaster risk management is essential to mitigate these potential threats.

Based on the reviewed literature, several measures could further reduce the risks associated with Lake Sarez and strengthen regional disaster preparedness. First, monitoring and early warning systems should be continuously upgraded and expanded to improve the rapid detection of changes in dam stability, lake levels, and surrounding slopes. Advances in satellite-based monitoring, GPS, and remote sensing technologies provide valuable opportunities to enhance existing observation networks and improve emergency response capabilities.

Second, regular geological, geotechnical, and seismic investigations are needed to improve understanding of the long-term stability of the Usoi Dam and surrounding mountain slopes. Particular attention should be given to evaluating the impacts of large earthquakes, landslides, and evolving hydrological conditions on dam integrity and overall hazard potential.

Third, disaster preparedness efforts should be strengthened through community education programs, evacuation planning, and emergency response training for populations living in potentially affected downstream areas. Improved public awareness and preparedness can significantly reduce vulnerability during emergency situations.

Given the transboundary nature of potential impacts, enhanced cooperation among Tajikistan and neighboring countries remains essential. Strengthening regional coordination through data sharing, joint risk assessments, and collaborative emergency response planning would improve preparedness for potential disaster scenarios affecting multiple countries.

Climate change considerations should also be integrated into future hazard management strategies. Continued glacier retreat, changing precipitation patterns, and the increasing frequency of extreme weather events may alter hydrological conditions in the Lake Sarez basin, requiring adaptive and forward-looking approaches to risk assessment and management.

Furthermore, the development of integrated multi-hazard modeling frameworks would improve understanding of the complex interactions among earthquakes, landslides, overtopping waves, and downstream flooding. Such models could support more accurate risk assessments, scenario analysis, and evidence-based decision-making.

Finally, potential engineering interventions, including controlled drainage systems and other risk-reduction measures, should be evaluated through comprehensive feasibility studies. Any future intervention should be guided by detailed geological, environmental, economic, and social assessments to ensure that risk reduction objectives are achieved without creating unintended consequences. Continued international scientific collaboration and technical support will remain important for advancing research, monitoring, and long-term disaster risk reduction efforts at Lake Sarez.

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