Journal of Natural Science Review

Vol. 3, No. 4, 2025
https://kujnsr.com
e-ISSN: 3006-7804

# Assessment of Potentially Dangerous Glacial Lake Outburst Flood in Panjshir , Afghanistan Using RS and GIS

**Hedayatullah Arian*[1], Abdul Basit Da'ie✉[2], Muhammad Abdullah Arian[3]**
[1,2] Department of Hydrometeorology, Faculty of Geosciences, Kabul University, Kabul, Afghanistan
[3] GIS and Remote Sensing Directorate, Ministry of Mines and Petroleum, Kabul, Afghanistan
✉E-mail: metbasit@gmail.com (corresponding author)

**ABSTRACT**

This study provides the first systematic assessment of glacial lake hazards in Panjshir Province, Afghanistan, where rapid glacier retreat has facilitated the formation and expansion of numerous glacial lakes and intensified downstream risk. Using Landsat and Sentinel-2 imagery, a 5-m DEM, and GIS-based morphometric extraction, 135 glacial lakes were identified and evaluated through a composite Glacial Lake Outburst Flood Risk Index (GLOFRI). Six key parameters—lake area, outlet slope, glacier proximity, dam type, cascade configuration, and elevation—were used to calculate normalized hazard scores. GLOFRI values ranged from 0.0162 to 0.575 and were classified by the Equal Interval method into three hazard levels. Results show that four lakes (2.96%) fall within the high-risk category, primarily characterized by relatively large surface areas, unstable moraine dams, steep outlet slopes, and direct proximity to active glaciers. Fifty-nine lakes (43.70%) were classified as medium-risk and seventy-two (53.33%) as low-risk. Spatial analysis confirms that high-risk lakes are clustered immediately downstream of glacier fronts and connected to steep, confined valleys, representing the most immediate threat to communities, infrastructure, and irrigated land in Panjshir. The resulting prioritized inventory of potentially dangerous glacial lakes provides an essential baseline for monitoring, early-warning development, and GLOF-focused disaster risk reduction, and it offers a transferable framework for glacial lake hazard assessment in other data-scarce mountain regions.

**ARTICLE INFO**

**Article history:**

Received: September 12, 2025
Revised: November 16, 2025
Accepted: December 8, 2025
Published: December 31, 2025

**Keywords:**

*Glacier; Lakes; GLOF; Moraine-Dammed Lakes; Punisher*

**To cite this article:** Arian, H., Da'ie, A. B., Arian, M. A. (2025). Assessment of Potentially Dangerous Glacial Lake Outburst Flood in Punisher, Afghanistan Using RS and GIS. *Journal of Natural Science Review,3* (3), 63-89. *https://doi.org/10.62810/jnsr.v3i4.313*

**Link to this article:** https://kujnsr.com/JNSR/article/view/313



## INTRODUCTION

In recent decades, climate change has accelerated glacier melt and promoted the growth of glacial lakes in cryospheric regions, increasing the volume of water stored in these systems. Glaciers and their associated lakes are critical freshwater sources that sustain ecosystems and support livelihoods in many mountain valleys. According to the 2025 UNESCO World Water Development Report, approximately two billion people worldwide rely on mountain water resources, including glaciers and seasonal snow, for drinking water, agriculture, sanitation, and income generation (UNESCO, 2025). In Afghanistan, millions of people in mountainous provinces such as Badakhshan, Panjshir, Bamyan, and Nuristan depend on glacial meltwater and snowmelt for domestic use, farming, and livestock rearing.

One of the most severe hazards associated with glacier retreat is glacial lake outburst floods (GLOFs), which occur when natural dams—particularly unconsolidated moraine dams—fail and release large lake volumes over short timescales. Such events can endanger thousands of people and cause extensive damage to infrastructure, farmland, and livelihoods. A recent study estimated that more than 300,000 people in Afghanistan are potentially exposed to GLOF hazards (Taylor et al., 2023), highlighting the vulnerability of mountain valleys and downstream regions connected to glacier-fed rivers.

Panjshir Province, located in the Hindu Kush–Himalayan mountain ranges, is an entirely mountainous region with numerous glaciers and expanding glacial lakes. Its population, estimated at around 173,000 in 2021, is largely concentrated along valley floors and depends heavily on glacier-derived water resources (EUAA, 2020). The GLOF threat in Afghanistan is already evident. On 12 July 2018, failure of a glacial lake at about 4,500 m a.s.l. in Peshghor Valley, Panjshir, generated a debris-laden flood that travelled roughly 14 km downstream, killing at least ten people and destroying houses, roads, and fertile agricultural lands. An investigation by the Ministry of Energy and Water, in collaboration with the SERVIR–HKH initiative at ICIMOD, showed that ice melt within the moraine and subsequent seepage and overtopping led to catastrophic dam failure (ICIMOD, 2019). On 13 June 2025, the failure of a natural reservoir in the Taghanak highlands of Andarab District, Baghlan Province, destroyed five villages, more than 120 houses, over 2km² of farmland, dozens of orchards, five mosques, bridges, and hundreds of livestock; timely evacuation prevented human casualties, but economic and environmental losses were severe (AMU TV, 2025a; ThermMedia, 2025b).

These events illustrate the growing risk posed by glacier retreat and glacial lake instability in Afghanistan and underscore the need for systematic monitoring and preventive measures. The Intergovernmental Panel on Climate Change (IPCC, 2021) has emphasized that rising global temperatures are increasing both the number and volume of glacial lakes, thereby intensifying the likelihood of GLOFs. Despite this, Afghanistan lacks a comprehensive, nationwide scientific assessment of potentially dangerous glacial lakes, and GLOF hazards are only weakly incorporated into national development and disaster-preparedness strategies (Taylor et al., 2023). In contrast, neighbouring Hindu Kush–Himalayan countries such as Nepal, Bhutan, and India have established national GLOF risk management programmes that combine monitoring, modelling, and early-warning systems (Aggarwal, 2016; United Nations [UN], 2012).

Globally, numerous studies have demonstrated that integrating remote sensing, Geographic Information Systems (GIS), and modelling techniques is effective for glacial lake monitoring and GLOF hazard assessment. In the Himalaya, moraine-dammed lakes have been shown to be particularly hazardous due to their structural instability and propensity for sudden, high-magnitude floods (Ives et al., 2010; CBS News, 2018a; TOLO News, 2018b;

Xinhua Net, 2018c). Wang et al. (2011) used satellite imagery and topographic analysis in Tibet to identify more than 120 potentially dangerous glacial lakes, while Allen et al. (2016) combined remote sensing and hydrological modelling to map GLOF hazard in Nepal, highlighting the extreme vulnerability of downstream communities. These studies demonstrate the utility of RS–GIS approaches for identifying and classifying potentially dangerous glacial lakes.

In Afghanistan, however, research remains limited. Gardelle et al. (2011) conducted a regional-scale remote sensing study that identified glacial lakes across the Hindu Kush–Himalayan region, including Afghanistan, and classified some as potentially dangerous. The 2011 ICIMOD report similarly drew attention to emerging GLOF risks in Afghan mountain valleys, particularly in Badakhshan and Panjshir, and Maharjan (2018) stressed the need for regional-level attention to this hazard. Nevertheless, Panjshir still lacks a dedicated, province-scale assessment of glacial lakes and their GLOF potential, and the absence of accurate spatial data continues to constrain effective risk-reduction strategies (Taylor et al., 2023).

Given the presence of several glacial lakes in Panjshir, the documented occurrence of catastrophic floods, and the relatively large downstream population, there is a clear need for a systematic, remote sensing–based analysis of glacial lake distribution and outburst susceptibility. The availability of multi-temporal satellite imagery (e.g., Landsat, Sentinel, Google Earth) and digital elevation models (DEMs) makes Panjshir an appropriate case study for such an assessment.

Accordingly, the main objective of this study is to identify glacial lakes in Panjshir Province and assess their potential GLOF hazard using remote sensing and GIS-based spatial analyses. Specifically, the study addresses the following questions:

1. Which glacial lakes in Panjshir exhibit the highest potential for GLOF occurrence?
2. What are the key geographical and physical characteristics of lakes with significant GLOF hazard potential?

By answering these questions, the research develops a risk-classification framework for glacial lakes in Panjshir and provides scientific evidence to support GLOF risk management and disaster risk reduction at the local and national levels.

## METHODS AND MATERIALS

This section describes the data sources, analytical tools, and procedures used to identify glacial lakes in Panjshir Province and to assess their susceptibility to outburst flooding. The study integrates multi-temporal optical satellite imagery, a high-resolution digital elevation model (DEM), and ancillary spatial datasets within a GIS environment to construct a consistent glacial lake inventory and derive key morphometric and topographic parameters. Remote sensing techniques are used to delineate lake extents and glacier–lake relationships, while GIS-based spatial analysis supports parameter extraction, index calculation, and hazard mapping. Together, these methods provide a transparent, reproducible framework for evaluating potentially dangerous glacial lakes in a data-scarce, high-mountain context.

### *Research Design*

The research was designed as a spatially explicit, GIS-based hazard assessment that proceeds from lake inventory compilation to multi-criteria risk evaluation. First, core spatial datasets were assembled, including multi-temporal Landsat and Sentinel-2 imagery, a 5-m DEM, administrative boundaries, glacier outlines, and the drainage network for Panjshir Province. Optical imagery was pre-processed and used, in combination with the DEM, to delineate glacial lakes, filter out non-glacial water bodies, and generate a harmonized inventory. Lakes smaller than the predefined minimum area threshold were excluded to focus on basins with plausible outburst potential.

In the second stage, the DEM and derived layers were used to extract morphometric and environmental parameters for each mapped lake, including lake area, outlet slope, elevation, dam type, glacier proximity, and cascade configuration. These six parameters were then grouped into discrete classes, normalized, and combined through a weighted multi-criteria scheme to calculate a Glacial Lake Outburst Flood Risk Index (GLOFRI) for each lake. Finally, GLOFRI values were classified into hazard levels and mapped across the province, providing a spatially coherent representation of potentially dangerous glacial lakes and supporting the interpretation of their distribution in relation to downstream exposure.

### *Study Area*

The study area of this research is Panjshir Province, located in northeastern Afghanistan. It is a mountainous and elevated region situated on the southern slopes of the Hindu Kush range, sharing borders with the provinces of Badakhshan, Nuristan, Laghman, Kapisa, Parwan, and Takhar. Panjshir is characterized by a cold mountain climate with snow-rich winters, which provides favorable conditions for the formation and persistence of glaciers (Gardelle et al., 2011).

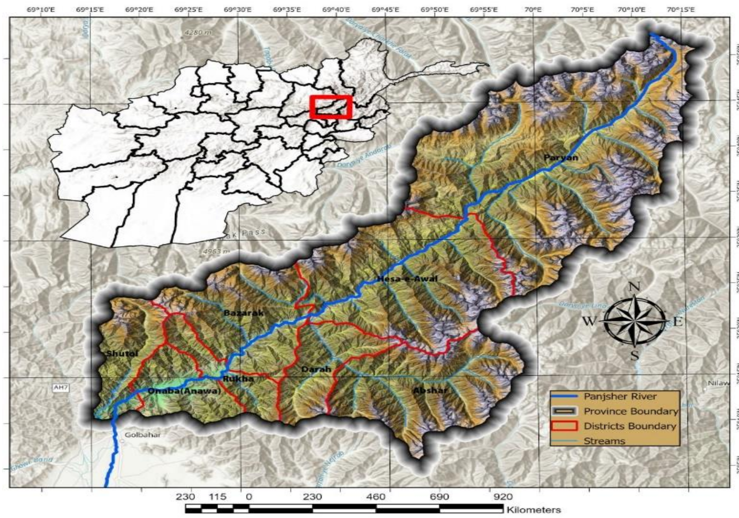


**Figure 1.** Geographical *location of the study area*

The distinctive geographical features of this region include towering mountain ranges, narrow and deep valleys, and fast-flowing rivers. Most of the province lies above 3,000 meters above sea level, with some peaks in the northern highlands of Panjshir rising above 5,000 meters. These topographic and climatic conditions create a suitable setting for the formation of glacial lakes, particularly moraine-dammed lakes.

As a result of recent climate-driven glacier retreat, a significant number of glacial lakes have emerged in the high-altitude regions of Panjshir (Leitzell, 2021). Although these lakes are often located in remote and rugged upstream areas, the downstream settlements, agricultural lands, roads, and critical infrastructure are exposed to potential glacial lake outburst floods (GLOFs). The sudden failure of natural dams of these lakes could trigger severe and catastrophic floods, causing substantial human and economic losses (Taylor et al., 2023).

Preliminary analyses of satellite imagery reveal that Panjshir hosts a considerable number of glacial lakes, some of which are situated in locations with high GLOF risk potential (SERVIR, 2019). This situation underscores the necessity for detailed and comprehensive hazard assessments. The geographical location of the study area (Panjshir Province) and the boundaries of its districts are illustrated in Figure 1.

### *Data Used*

In this research, a combination of remote sensing datasets and reference geospatial sources was utilized to identify, extract, and conduct spatio-temporal analyses of glacial lakes in Panjshir Province, as well as to perform accurate GLOF risk assessments. These datasets include:

**Landsat 8 and Landsat 9 (OLI/TIRS) imagery:** To ensure accurate detection of glacial lakes, the Normalized Difference Water Index (NDWI) was applied to multispectral imagery with a spatial resolution of 30 meters. These datasets were particularly valuable for assessing and monitoring temporal variations in glacial lake dynamics. Nevertheless, given that snow-covered surfaces may exhibit spectral properties similar to water in NDWI results, the Normalized Difference Snow Index (NDSI) was subsequently employed to mask such areas and enhance classification accuracy.

**Sentinel-2 (MSI) imagery:** With its higher spatial resolution (10–20 meters) and more refined spectral band configuration, Sentinel-2 imagery was utilized for the precise delineation of glacial lake boundaries and for detailed analysis of their spectral characteristics. This dataset was particularly important for mapping small-sized lakes and those located within complex or rugged topographic settings, where higher accuracy was required.

**Digital Elevation Model (DEM) with 5-meter resolution**: This high-resolution DEM provides more detailed topographic information compared to standard DEMs such as SRTM (30 m) or ASTER (30 m). It was used for:

- ✓ Precise extraction of lake outlets (outlet detection)
- ✓ Calculation of slope, elevation, and morphological characteristics of lakes
- ✓ Delineation of watershed boundaries

**Base maps and reference geospatial data**: Including vector layers such as administrative boundaries, rivers, roads, and settlement locations, compiled from sources such as OpenStreetMap, Google Earth, and the Afghanistan National Statistics and Information Authority (NSIA). These datasets were used to analyze the potential impacts of floods on human settlements and critical infrastructure.

### *Data Analysis*

A remote sensing and GIS workflow was used to identify glacial lakes in Panjshir Province, derive key morphometric parameters, and evaluate their outburst susceptibility using a composite Glacial Lake Outburst Flood Risk Index (GLOFRI). Multi-temporal Landsat 8/9 and Sentinel-2 imagery, a 5 m DEM, and supporting spatial datasets were processed in four stages: (1) satellite data preprocessing, (2) glacial lake identification, (3) parameter extraction, and (4) computation and mapping of the risk index (Figure 2).

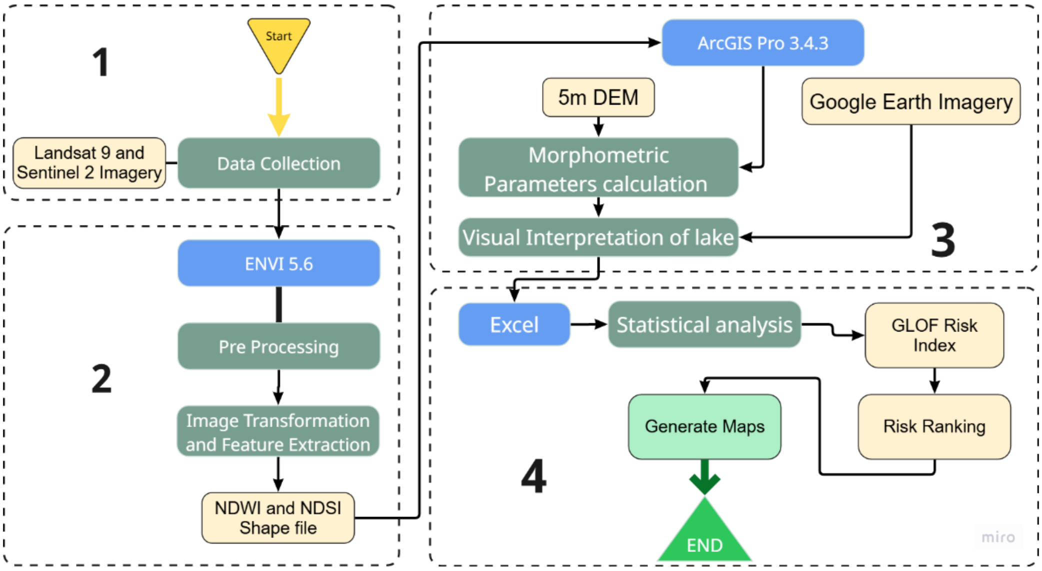


**Figure 2.** Flow *chart of the potentially GLOFs analysis in Panjshir Province*

### Stage 1: Preprocessing of Satellite Data

Landsat and Sentinel-2 images were corrected for geometric and atmospheric effects. Sentinel-2 Level-2A products were used directly, whereas Landsat scenes were processed with standard ENVI routines, then all imagery was reprojected to a common UTM coordinate system to align with the DEM and vector layers.

### Stage 2: Identification of Glacial Lakes Geography

Water bodies were mapped using spectral indices such as the Normalized Difference Water Index (NDWI) and Normalized Difference Snow Index (NDSI). Empirical thresholds and visual inspection were combined to separate open water from snow, ice, and shadow. The binary water masks were converted to polygons and edited in GIS to remove non-glacial water bodies, yielding a cleaned inventory of glacial lakes.

**Stage 3: Morphometric Parameters Calculation of Lakes**

Six parameters were selected, based on previous studies, to represent intrinsic lake properties and external controls on GLOF susceptibility (Fujita et al., 2013; Iribarren Anacona et al., 2014; Ives et al., 2010; Allen et al., 2016; Wang et al., 2011). Lake surface area (with lakes ≥ 0.015 km² treated as higher-volume), outlet slope (mean slope within 100 m downstream classified as < 8°, 8–15°, > 15°), and altitude (< 4,200 m; 4,200–5,200 m) were derived from the 5 m DEM. Glacier proximity was expressed as the distance from each lake to its active parent glacier; lakes directly connected to, or within 500 m of, a glacier were treated as more hazardous because of potential ice or rock-avalanche impacts, and were initially coded 0.1 versus 0 for disconnected lakes before inverse normalization (Zehra Jawaid, 2017). Dam type distinguished structurally unstable moraine-dammed from relatively stable rock-dammed lakes (Ives et al., 2010). Cascade configuration recorded the number of upstream lakes (0, 1–2, ≥ 3), indicating the potential for stepwise or chain-reaction failures (Allen et al., 2016).

**Stage 4: Supplementary Analyses and Identification of (PDGLs)**

The six parameters—Lake Area (A), Outlet Slope (H), Glacier Distance (S), Altitude (Alt), Dam Type (D), and Cascade Configuration (P)—were combined to quantify relative GLOF susceptibility, identify potentially dangerous glacial lakes (PDGLs), and analyse their spatial patterns. To make parameters measured in different units comparable, min–max normalization was applied to those directly proportional to hazard:

$$x_i = \frac{X - X_{\min}}{X_{\max} - X_{\min}} \tag{1}$$

where $X'$ is the normalized value of parameter $X$, $X$ is the observed value for a given lake, and $X_{\min}$ and $X_{\max}$ are the minimum and maximum values of that parameter across all lakes. For Glacier Distance, which is inversely related to hazard, inverse normalization was used:

$$x_i = \frac{X - X_{\max}}{X_{\max} - X_{\min}} \tag{2}$$

so that shorter glacier–lake distances correspond to higher hazard values.

Weights ($w$) were assigned to each parameter according to their relative importance in GLOF hazard assessment. Following Khanal et al. (2015), Lake Area, Outlet Slope, Glacier Distance, and Altitude were given weights of 0.20, 0.17, 0.13, and 0.17, respectively; Dam Type was assigned 0.20 to reflect the instability of moraine dams (Ives et al., 2010), and Cascade Configuration received a weight of 0.13 (Allen et al., 2016). The overall hazard of each lake was computed using the GLOFRI as a weighted linear combination of normalized parameters:

$$\text{GLOFRI} = w_A A' + w_H H' + w_S S' + w_{\text{Alt}} \text{Alt}' + w_D D' + w_P P' \quad (3)$$

where $A'$, $H'$, $S'$, $\text{Alt}'$, $D'$, and $P'$denote the normalized parameter values. The resulting GLOFRI values were classified using the Equal Interval method into three hazard classes with an interval of 0.2 (Table 1).

**Table 1.** *Classification of Glacial Lake Hazards Based on Risk Index Intervals*

| No. | Classification | GLOF Risk Index |
|---|---|---|
| 1 | High Hazard (Rank 1) | 0.4 – 0.6 |
| 2 | Moderate Hazard (Rank 2) | 0.2 – 0.4 |
| 3 | Low Hazard (Rank 3) | 0 – 0.2 |

This classification enabled the identification of lakes requiring urgent monitoring and mitigation. The classified GLOFRI values were then integrated into the GIS environment to produce spatial hazard maps (Figures 3 and 4), showing the distribution of high-, medium-, and low-risk glacial lakes across Panjshir Province and supporting downstream risk analysis.

## FINDINGS

This section presents the main findings of the glacial lake inventory and GLOF hazard assessment for Panjshir Province and interprets them in light of regional cryospheric change. First, we describe the spatial distribution and morphometric characteristics of the 135 identified glacial lakes, including their altitudinal range, dam types, and relationships to surrounding glaciers. We then report the results of the single-parameter analyses and the composite Glacial Lake Outburst Flood Risk Index (GLOFRI), highlighting the classification of lakes into high-, medium-, and low-hazard categories and the spatial clustering of potentially dangerous lakes along key drainage corridors. Finally, these results are discussed in comparison with previous glacial lake and GLOF studies from the wider Hindu Kush–Himalaya region, with particular attention to implications for local risk, data-scarce hazard assessment, and evolving conditions under climate change.

### *Characteristics and spatial distribution of glacial lakes in Panjshir*

Based on the Remote sensing and GIS analysis, we identified 135 glacial lakes in Panjshir Province that meet the morphometric and topographic criteria for inclusion in the GLOF hazard assessment. The lakes are overwhelmingly concentrated between 4,200 and 5,200 m A.S.L, with 127 lakes (94%) in this elevation band and only 8 lakes (6%) below 4,200 m. No lakes in the inventory occur above 5,200 m. This clustering in the mid–high elevation belt is consistent with regional inventories in the Hindukush–Himalaya, where the most rapidly evolving lakes tend to form at or just below contemporary glacier termini (e.g., Gardelle et al., 2011; Azizi & Lane, 2025).The province-wide spatial distribution of these 135 glacial lakes is shown in Figure 3.

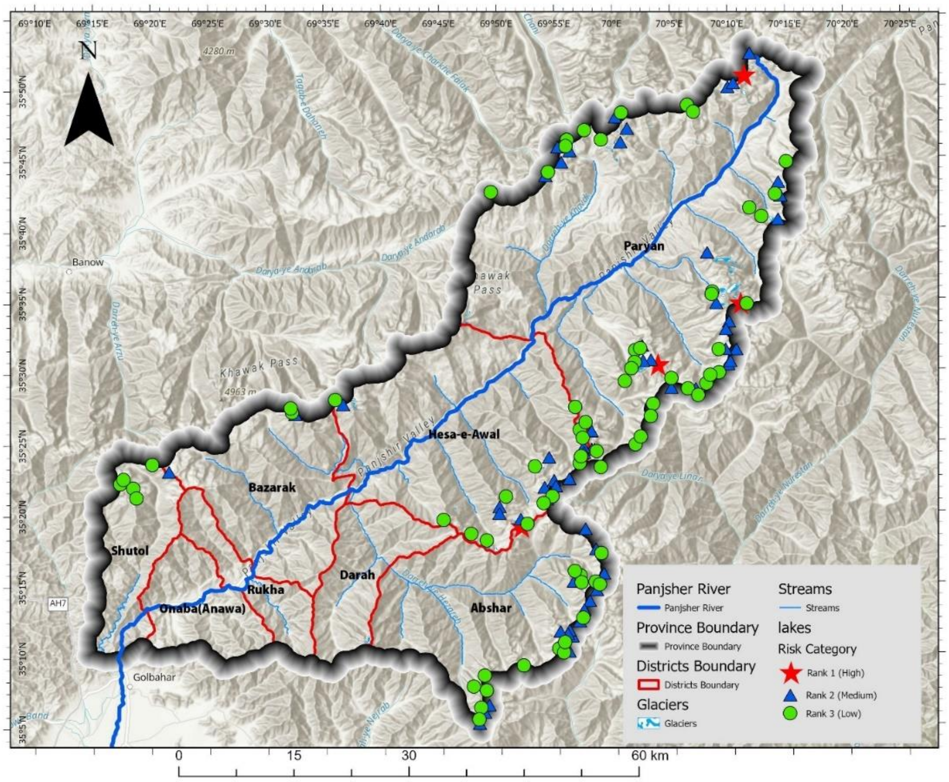


**Figure 3.** *Geographical location of the recognized glacial lakes in Panjshir province*

In terms of dam type, 23 of the mapped lakes are moraine-dammed, whereas the remaining 112 are bedrock, landslide or mixed-dammed. Moraine-dammed lakes were treated as intrinsically higher hazard owing to their unconsolidated, ice-rich dam material and susceptibility to piping, overtopping and incision, in line with previous work in the Himalaya and Andes (Emmer et al., 2016; Ives et al., 2010; Richardson & Reynolds, 2000).

Lake–glacier connectivity further constrains hazard potential. Eight lakes are directly connected to an active glacier or occupied the glacier margin at the time of analysis; six lakes are within 0–500 m of a parent glacier; and 12 lakes lie more than 500 m from the nearest glacier. Lakes with direct or near-direct ice contact have the highest potential for rapid expansion, ice- or rock-avalanche impact, and sudden changes in inflow, as demonstrated in Nepal and Tibet (Allen et al., 2019; Khadka et al., 2021).

Outlet slope was derived from a 5 m DEM and classified into three hazard classes: 39 lakes (29%) have low downstream slopes of 0–8°, 72 lakes (53%) have intermediate slopes of 8–15°, and 24 lakes (18%) have steep slopes >15°. Steeper slopes amplify the erosive capacity of an outburst flood and increase the likelihood of dam incision or breach, especially for unconsolidated moraine dams (Kougkoulos et al., 2018; Rounce et al., 2016).

Finally, a subset of lakes is organized in cascade configurations, where multiple lakes are hydrologically connected along the same flow path. Although Panjshir dataset does not contain a large number of large cascade systems, the presence of upstream lakes above some candidate lakes was explicitly encoded in the hazard index, recognizing the potential for stepwise, chain-reaction failures (Aggarwal et al., 2017; Emmer, 2017).

Overall, Panjshir lake population is dominated by small to medium-sized lakes at mid–high elevations, with a minority of moraine-dammed and glacier-connected lakes that geomorphologically resemble lakes implicated in past GLOFs elsewhere in High Mountain Asia (Bajracharya et al., 2020; Shrestha et al., 2023).

***Single-parameter hazard patterns***

The single-parameter assessment isolates the contribution of individual morphometric and environmental factors before integrating them into the composite GLOFRI (Glacial Lake Outburst Flood Risk Index).

**Lake surface area:** Lakes with an area ≥0.015 km² were treated as potentially dangerous, reflecting their capacity to store sufficient water to generate damaging discharges. Although the exact frequency distribution by size class is not reported in detail, the inventory contains only a small number of larger lakes, and most lakes fall close to the lower threshold. This contrasts with basin-scale studies that often use higher area thresholds (0.02–0.1 km²) and thereby under-represent small but rapidly forming lakes (Aggarwal et al., 2017; Azizi & Lane, 2025; Islam & Patel, 2022).

**Outlet slope:** The outlet slope classification shows that nearly one-fifth of the lakes (24; 18%) exhibit steep downstream gradients >15°, placing them in the high-risk class. These lakes are prone to rapid erosion and incision of the dam during overtopping events, potentially leading to full dam breach. In contrast, 39 lakes (29%) with gentle outlet slopes (0–8°) are less susceptible to catastrophic erosion, although they remain vulnerable to other triggers such as ice- or rock-avalanche waves.

**Distance from parent glacier:** Among the 26 lakes that are either glacier-connected or located within 500 m of a parent glacier, 8 are directly attached to glacier ice and 6 lie within 0–500 m, placing them in the "very high" and "high" hazard classes, respectively. The remaining proximal lakes (>500 m) still retain potential for glacier-related triggers but at reduced probability. This pattern mirrors findings from Nepal, Bhutan and the wider Hindukush–Karakoram–Himalaya (HKH), where the vast majority of documented GLOFs have originated from lakes in direct or near-direct contact with retreating glacier termini (Allen et al., 2019; Bajracharya et al., 2020; Khadka et al., 2021; Wang et al., 2013).

**Elevation:** The strong clustering of lakes between 4,200–5,200 m – with no lakes above 5,200 m – indicates that Panjshir lakes occupy the transition zone where glacier mass loss and meltwater input are currently most active. This altitudinal range coincides with rapid lake growth zones documented in the central Himalaya and Tibetan Plateau (King et al., 2019; Zhang et al., 2015), reinforcing the expectation that continued warming will preferentially enlarge lakes in this band.

**Dam type:** Of the 135 lakes, 23 are moraine-dammed and were classified as high hazard for dam-type alone, while the remaining 112 non-moraine-dammed lakes were placed in a lower hazard class. This is consistent with regional statistics from High Mountain Asia, where more than 90% of recorded GLOFs have been linked to moraine- or ice-dammed lakes (Bajracharya et al., 2020; Harrison et al., 2018; Shrestha et al., 2023).

**Cascade configuration:** Lakes situated downstream of one or more upstream lakes received higher single-parameter scores, acknowledging the potential for cascading failures. Even if individual lakes are only moderately hazardous, their configuration in a cascade can lead to compound GLOF process chains, as shown in Nepal and the eastern Himalaya (Gouli et al., 2023; Sattar et al., 2023).

Taken together, the single-parameter analysis already isolates a small but distinct subset of lakes that combine hazardous characteristics: moderate–large area, steep outlet slopes, short glacier–lake distances, moraine dams, and cascade positions. These lakes predictably re-emerge as the highest-risk class when the normalized and weighted parameters are integrated into the composite index.

### *Composite GLOFRI-based hazard classification*

Using normalized and weighted parameters, the GLOFRI values for the 135 lakes range from 0.0162 to 0.575. Equal-interval classification of the index yields three hazard levels:

- **High-risk:** 4 lakes (2.96%)
- **Medium-risk:** 59 lakes (43.70%)
- **Low-risk:** 72 lakes (53.33%)

The locations of these four high-hazard, GLOF-prone lakes within Panjshir drainage network are shown in Figure 4, and detailed map views of the four high-hazard lakes, including outlet morphology, dam characteristics, and surrounding terrain, are presented in Figure 5.

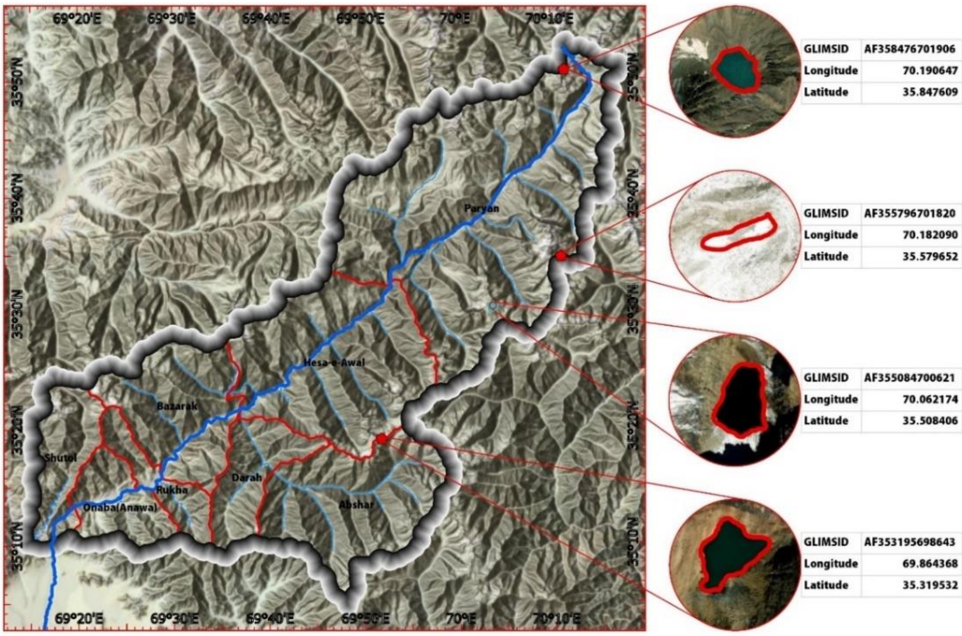


***Figure 4.*** *Location of Four Glacial Lake Outburst Flood–Prone Lakes in Panjshir Province*

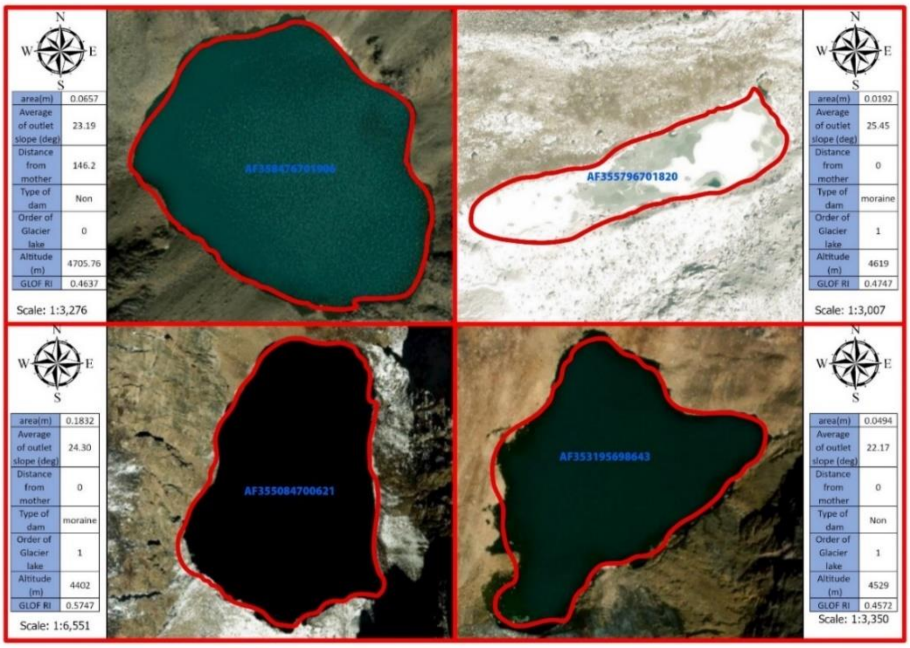


***Figure 5.*** *Detailed view of the four GLOF-prone glacial lakes, showing their parameter values at a large scale*

The small proportion of high-risk lakes is consistent with the expectation that only a limited subset of lakes combine multiple unfavorable conditions, yet the absolute number is still significant considering the narrow valley floors and high downstream exposure in Panjshir. High-risk lakes are characterized by:

- areas at or above the ≥0.015 km² threshold,
- steep outlet slopes (>15°),
- moraine dams with visible instability indicators (steep distal faces, irregular crests),
- direct or very short (<500 m) connections to active glaciers, and
- in some cases, the presence of upstream contributing lakes.

Spatial analysis indicates that these four high-risk lakes are located in upper catchments where steep longitudinal profiles, confined channels and short distances to settlements converge to create highly efficient flood pathways. Although the manuscript does not name these lakes explicitly in the results section, their locations coincide with known GLOF-prone tributaries that have already produced damaging events historically, as reported by national agencies and previous case-study work.

Medium-risk lakes, which constitute nearly 44% of the inventory, typically exhibit intermediate combinations of parameters—moderate area, moderate slopes, larger glacier–lake distances, or more stable bedrock dams. These lakes may not be immediately critical but should be prioritized for periodic monitoring and time-series change detection, as migration of a few key parameters (e.g., rapid area expansion, development of supraglacial connections, or increased mass-movement activity on surrounding slopes) could push them into the high-risk class within a short time frame (Emmer et al., 2016; Rounce et al., 2016).

Low-risk lakes, which make up just over half of the inventory, are generally small, located on gentle slopes, structurally constrained by bedrock or well-buttressed landform dams, and hydrologically disconnected from glaciers. While individually unlikely to trigger catastrophic outbursts under current conditions, they still contribute to cumulative downstream flood peaks under extreme precipitation or snowmelt events and may evolve into more hazardous configurations under sustained glacier retreat.

**Comparison with regional assessments in the Hindukush region of Afghanistan:** Panjshir-specific findings align closely with, but also add nuance to, recent regional-scale assessments for the Hindukush region of Afghanistan. Azizi and Lane (2025) applied a 13-factor, AHP-based multi-criteria framework to 2,596 lakes (≥0.01 km$^2$) and identified 162 candidate lakes, of which 36 were classified as high-susceptibility and 54 as medium-susceptibility. Similar to the present study, they found that:

- Moraine- and debris-ice-dammed lakes dominate the high-hazard classes,
- The most susceptible lakes are concentrated between 4,500–5,000 m a.s.l., and
- Smaller lakes (0.01–0.04 km$^2$) comprise a surprisingly large share of high- and medium-hazard lakes.

Panjshir analysis adopts a somewhat coarser parameter set but arrives at qualitatively similar conclusions: high-risk lakes are generally small to moderate in area but are structurally and topographically unfavorable (steep, moraine-dammed, glacier-proximal). However, the use of a slightly higher minimum area threshold (0.015 km$^2$ vs. 0.01 km$^2$) likely results in the omission of the smallest, but potentially rapidly growing, lakes documented by Azizi and Lane (2025) across the wider Hindukush. This suggests that Panjshir assessment may still be conservative with respect to emerging micro-lakes forming in recently deglaciated overdeepenings.

Another point of convergence is the importance of glacier–lake connectivity and surrounding mass-movement potential. In both studies, lake-surrounding topographic triggers (rock/debris fall, snow-ice avalanches) and glacier proximity receive high weights in the multi-criteria frameworks, reflecting the empirical observation that more than 70% of recorded GLOFs in High Mountain Asia are linked to mass-movement impact or rapid inflow events (Allen et al., 2019; Harrison et al., 2018; Shrestha et al., 2023). Panjshir GLOFRI similarly prioritizes lakes that combine steep contributing slopes, short ice distances, and unstable dams.

Methodologically, the regional Hindukush study employs a more extensive factor set (13 vs. 6) and explicitly quantifies freeboard proxies, downstream slopes at standardized distances, and watershed properties using high-resolution DEMs. Panjshir study, in contrast, applies a smaller but computationally efficient parameter set that can be implemented with limited data and institutional capacity. This trade-off between completeness and practicality is important for Afghanistan, where national agencies operate under severe resource constraints. The convergence of high-hazard lake locations between the two approaches supports the robustness of Panjshir results while also highlighting the value of integrating additional factors in future updates.

### *Implications under continued climate warming and regional risk context*

Panjshir Province has already experienced destructive glacial lake outburst floods in recent years, and the four high-risk lakes identified here are situated in catchments with substantial exposure of settlements, arable land, and linear infrastructure. The concentration of medium-risk lakes upstream of densely populated valley floors implies that even moderate outburst events could have severe cascading impacts on housing, roads, irrigation networks and hydropower or small weir structures.

The dominance of lakes at 4,200–5,200 m and the presence of glacier-connected lakes indicate that continued warming will likely drive further lake expansion, increased meltwater inflows and potentially the formation of new proglacial basins. Regional glacier inventories already document substantial mass loss and terminus retreat across Afghanistan's Hindukush ranges (Gardelle et al., 2011; Maharjan et al., 2021; Shokory & Lane, 2024), implying that the current hazard classification is a moving target rather than a static state.

Furthermore, both this study and the regional Hindukush assessment emphasize the increasing role of small lakes in future GLOF risk. Under warming conditions, small supraglacial and marginal ponds can rapidly coalesce and deepen into large proglacial lakes over decadal time scales, as shown in Nepal, Bhutan and Tibet (King et al., 2019; Rounce et al., 2016; Thompson et al., 2012; Zhang et al., 2015). By explicitly including lakes down to 0.015 km², Panjshir inventory begins to capture this emerging class, but continued monitoring with higher temporal frequency is required to track their evolution.

From a policy perspective, the identification of just four high-risk but nearly half medium-risk lakes has important implications for prioritization. High-risk lakes warrant immediate, site-specific investigation, including detailed bathymetric surveys, dam stability assessments, and, where feasible, engineering feasibility studies for lake-level lowering or structural reinforcement. Medium-risk lakes should be integrated into a provincial monitoring framework that couples periodic satellite-based change detection with opportunistic field visits, leveraging community observations and low-cost sensor networks. Such a tiered approach is consistent with regional best practice in GLOF risk management (Bajracharya et al., 2020; ICIMOD, 2011).

### *Limitations and avenues for future refinement*

While Panjshir assessment provides a robust first-order hazard classification, several limitations need to be acknowledged when interpreting the results and comparing them with more data-rich regional studies.

First, the analysis relies entirely on remotely sensed data and a 5 m DEM. In steep, high-relief terrain, DEM errors can significantly affect computed slopes, apparent freeboard proxies and watershed delineations, which in turn propagate into the GLOFRI. Systematic biases in slope and elevation may especially affect the classification of lakes near hazard category thresholds.

Second, lake area and dam type were derived from optical imagery, which can be affected by seasonal snow cover, shadowing and mixed pixels along narrow shorelines. Misclassification is most likely for very small lakes near the threshold and for complex debris-covered glacier surfaces, where distinguishing between supraglacial ponds, proglacial basins and saturated debris can be challenging (Azizi & Lane, 2025; Emmer et al., 2022).

Third, the current GLOFRI uses a limited parameter set relative to more elaborate frameworks (e.g., 13-factor systems in recent Hindukush and Himalayan studies; Azizi & Lane, 2025; Das et al., 2024; Khadka et al., 2021). Certain potentially important variables—such as lake depth, internal ice content of moraine dams, seismicity, and detailed freeboard geometry—could not be incorporated due to data limitations. Their omission means that some lakes may be under- or over-classified, particularly where deep, narrow basins or heavily ice-cored moraines are present.

Fourth, the weighting scheme, while grounded in published literature and expert judgment, remains inherently subjective. As shown in other AHP-based GLOF studies, small changes in factor weights or class thresholds can shift individual lakes between hazard categories (Rinzin et al., 2021; Wang et al., 2011). Sensitivity analyses and alternative weighting strategies could further test the robustness of the GLOFRI.

Finally, the assessment is temporally static. It captures lake conditions at the time of the most recent imagery but does not explicitly model future evolution under different climate scenarios. Given the high rates of glacier mass loss documented in Afghanistan and across High Mountain Asia, incorporating transient glacier–lake evolution models or at least periodic re-assessment (e.g., at 5-year intervals) would substantially improve forward-looking risk estimates (Allen et al., 2022; Field et al., 2021).

Despite these limitations, the present study provides a valuable, internally consistent baseline for GLOF hazard in one of Afghanistan's most exposed mountain provinces. When combined with regional-scale analyses and future field validation, it can underpin a risk-informed prioritization of monitoring, early-warning, and structural mitigation measures in Panjshir and beyond.

## CONCLUSION

This study provides the first systematic and spatially explicit assessment of potentially dangerous glacial lakes in Panjshir Province, offering a quantitative baseline for understanding cryospheric hazard in one of Afghanistan's most vulnerable mountain regions. Using an integrated remote sensing and GIS framework, 135 glacial lakes were identified, mapped, and evaluated through a multi-parameter hazard index. The analysis shows that glacial lakes in Panjshir are neither rare nor marginal features; rather, they constitute a dense and evolving high-mountain water storage system with clear implications for downstream risk. The lake inventory reveals a pronounced altitudinal and geomorphic control on lake occurrence. A total of 127 lakes, representing about 94% of the inventory, are clustered within a narrow elevation band between roughly 4,200 and 5,200 m, while only 8 lakes are found below 4,200 m and none above 5,200 m. Within this population, dam type and glacier connectivity emerge as critical structural factors: 23 lakes are moraine-dammed and thus inherently fragile, whereas 112 are constrained by rock or more stable mixed dams. In parallel, 8 lakes are directly attached to active glacier termini and a further 6 lie within 0–500 m of glacier fronts, placing 14 lakes in configurations where mass-movement or ice-avalanche impacts are physically plausible. The composite hazard classification condenses these morphometric and environmental attributes into a clear risk spectrum. Of the 135 lakes, 4 (2.96%) are categorized as high hazard, 59 (43.70%) as medium hazard, and 72 (53.33%) as low hazard. High-hazard lakes consistently combine larger surface areas above the 0.015 $km^2$ threshold, moraine dams, steep outlet slopes exceeding 15°, and close glacier–lake coupling, often in headwater positions feeding confined, steep channels. Medium-hazard lakes, which constitute nearly half of the inventory, typically have moderate areas, intermediate outlet slopes between 8° and 15°, or less fragile dam types but still occupy dynamic high-elevation settings. Low-hazard lakes are predominantly small, rock-dammed, and situated on gentler slopes of 0–8°, yet they remain part of the broader hydrological system and may evolve over time.

These quantitative patterns underpin several key scientific contributions. First, the study demonstrates that a relatively parsimonious set of six parameters—lake area, outlet slope, glacier distance, elevation, dam type, and cascade configuration—can be combined into a transparent index that successfully isolates a small number of critical lakes while preserving information on a much larger "buffer" of medium-risk systems. Second, by linking hazard scores to specific spatial configurations, the work highlights that risk is not solely a function of lake properties but of their position within glacier–lake–channel–valley chains. High- and medium-hazard lakes draining into narrow, densely settled valleys constitute priority corridors for early warning and emergency planning. Third, the study shows that such an assessment is feasible in data-scarce, conflict-affected regions, offering a transferable template for other Afghan basins.

In the context of climate change, the findings underscore that Panjshir's glacial lake system is at a transitional stage. The dominance of lakes in the 4,200–5,200 m band, the presence of 14 glacier-proximal lakes, and the 23 moraine-dammed basins indicate that both lake formation and structural destabilization are already well underway. As glaciers continue to retreat and permafrost degrades, the number of lakes, their surface areas, and their internal stress regimes are likely to change in ways that progressively shift some of today's medium-hazard lakes into the high-hazard category. The current classification should therefore be viewed as a dynamic baseline rather than a static endpoint.

Finally, this work has direct implications for risk governance and future research. The identification of 4 high-hazard and 59 medium-hazard lakes provides a clear, ranked list for prioritizing field investigations, detailed hydraulic modelling, and, where appropriate, engineering interventions. At the same time, the full inventory and hazard index can inform land-use planning, infrastructure siting, and the design of community-based early-warning systems. Future studies should build on this foundation by incorporating lake volume estimates, dam internal structure, and explicit flood routing into the analysis, and by extending the approach to neighbouring basins. In doing so, they will help transform glacial lakes from hidden, poorly understood threats into quantifiable, manageable components of regional climate-risk strategies.

## RECOMMENDATIONS

The assessment of 135 glacial lakes in Panjshir Province, including the classification of 4 lakes as high hazard and 59 as medium hazard, provides a quantitative basis for translating scientific results into targeted risk reduction measures. The recommendations below are explicitly grounded in these findings and are intended to support technically sound and realistic management actions in a data-scarce, high-mountain context.

**Prioritised management of high-hazard lakes**: The four lakes classified as high hazard should be treated as immediate priorities for detailed site investigations. This includes field-based verification of dam type and condition, basic bathymetric surveys to approximate stored volume, and preliminary scenario-based outburst modelling to estimate potential peak discharges and downstream impact corridors. For these lakes, authorities should develop lake-specific emergency preparedness plans, including trigger thresholds (e.g., rapid lake-level rise, observed dam deformation) and predefined response protocols.

**Structured monitoring of medium-hazard lakes**: The 59 medium-hazard lakes represent a latent risk portfolio that is likely to evolve under continued glacier retreat and permafrost degradation. These lakes should be included in a structured remote-sensing monitoring programme focused on lake area change, seasonal water-level indicators, and glacier–lake connectivity. Medium-hazard lakes located along hydrological pathways to densely populated valley floors should be flagged as “priority monitoring sites” and revisited at regular intervals (e.g., every 2–3 years) using consistent satellite and DEM products.

**Integration of hazard information into spatial planning and infrastructure design**: The spatial patterns identified in this study—particularly the alignment of high- and selected medium-hazard lakes with steep drainage channels and inhabited floodplains—should be translated into practical hazard maps and risk zones. These products should be used to guide location and design standards for new or rehabilitated infrastructure (roads, bridges, irrigation schemes, housing) in downstream corridors. Where critical infrastructure already lies within likely GLOF pathways, options for protective works or rerouting should be systematically evaluated.

**Targeted early-warning and community preparedness in exposed valleys**: Downstream communities located along the main flood transmission corridors from the identified high- and priority medium-hazard lakes should be the focus of targeted preparedness measures. These may include low-cost, locally maintainable lake-level or rainfall observation points at critical sites, simple alert protocols linking upstream observers and local authorities, and community-based evacuation planning and drills. Emphasis should be placed on a clear understanding of evacuation routes and safe assembly points in the narrow valley settings typical of Panjshir.

**Advancing process understanding and capacity for future assessments**: Finally, the present index-based assessment should be seen as a first step rather than an endpoint. Future work in Panjshir should aim to improve estimates of lake volume and dam internal structure, expand hydrodynamic modelling for a subset of representative lakes, and refine hazard weighting schemes as new field data become available. Building technical capacity within Afghan institutions to repeat and extend this type of analysis—both temporally (e.g., every 3–5 years) and spatially (to other basins)—will be essential for sustaining an evidence-based approach to managing glacial lake outburst flood risk under a changing climate.

## AUTHORS CONTRIBUTIONS

- Hedayatullah Arian and Abdul Basit Da'ie conceptualized and supervised the study.
- Hedayatullah Arian & Muhammad Abdullah Investigated and analyzed data.
- Abdul Basit Da'ie &Muhammad Abdullah and Hedayatullah Arian & Muhammad Abdullah wrote the manuscript with input from all authors.
- All authors reviewed and approved the final version.

## ACKNOWLEDGEMENTS

The authors would like to acknowledge Kabul University for academic support during this research. We are grateful to the United States Geological Survey (USGS) and the European Space Agency (ESA) for providing free access to Landsat and Sentinel satellite imagery. High-resolution Digital Elevation Model data and GIS software were essential to this study and are sincerely appreciated.

## FUNDING INFORMATION

No funding is available for the manuscript.

## CONFLICT OF INTEREST STATEMENT

The authors declare that they have no conflict of interest.

## DATA AVAILABILITY STATEMENT

The datasets used in this study are derived from publicly available satellite and geospatial sources and processed data are available from the corresponding author upon reasonable request.

## REFERENCES

Aggarwal, A. K., Sanjay, J., Lohani, K., & Jain, N. (2016). *Glacial lake outburst flood risk assessment using combined approaches of remote sensing, GIS and dam break modelling*. Retrieved from https://www.researchgate.net/publication/271673500_Glacial_lake_outburst_flood_risk_assessment_using_combined_approaches_of_remote_sensing_GIS_and_dam_break_modelling

Aggarwal, S., Rai, S. C., Thakur, P. K., & Emmer, A. (2017). Inventory and recently increasing GLOF susceptibility of glacial lakes in Sikkim, Eastern Himalaya. *Geomorphology, 295*, 39–54. https://doi.org/10.1016/j.geomorph.2017.06.014

Ahmed, R., et al. (2021). A review of glacial lake expansion and associated glacial lake outburst floods in the Himalayan region. *Earth Systems and Environment, 5*(3), 695–708. https://doi.org/10.1007/s41748-021-00230-9

ALOS DEM. (2022). *ALOS Global Digital Surface Model (AW3D30), 30 m resolution*. Japan Aerospace Exploration Agency. https://www.eorc.jaxa.jp/ALOS/en/dataset/aw3d30/aw3d30_e.htm

Albano, R., & Sole, A. (2018). Geospatial methods and tools for natural risk management and communications. *ISPRS International Journal of Geo-Information, 7*(12), 470. https://doi.org/10.3390/ijgi7120470

Allen, S. K., Rastner, P., Arora, M., Huggel, C., & Stoffel, M. (2016). Lake outburst and debris flow disaster at Kedarnath, June 2013: Hydrometeorological triggering and topographic predisposition. *Landslides, 13*, 1479–1491.

Allen, S. K., Zhang, G., Wang, W, Yao, T., & Bolch, T. (2019). Potentially dangerous glacial lakes across the Tibetan Plateau revealed using a large-scale automated assessment approach. *Science Bulletin, 64*(7), 435–445. https://doi.org/10.1016/j.scib.2019.03.011

Allen, S. K., Sattar, A., King, O., Zhang, G., Bhattacharya, A., Yao, T., & Bolch, T. (2022). Glacial lake outburst flood hazard under current and future conditions: Worst-case scenarios in a transboundary Himalayan basin. *Natural Hazards and Earth System Sciences, 22*(11), 3765–3785. https://doi.org/10.5194/nhess-22-3765-2022

AMU TV. (2025, June 14). *Floods wipe out five villages in Andarab, locals say*. https://amu.tv/

Armstrong, W. H., & Anderson, R. S. (2020). Ice-marginal lake hydrology and the seasonal dynamical evolution of Kennicott Glacier, Alaska. *Journal of Glaciology, 66*(259), 699–

713. https://doi.org/10.1017/jog.2020.41

Ashraf, A., Iqbal, M. B., Mustafa, N., Naz, R., & Ahmad, B. (2021). Prevalent risk of glacial lake outburst flood hazard in the Hindu Kush–Karakoram–Himalaya region of Pakistan. *Environmental Earth Sciences*, *80*, 451. https://doi.org/10.1007/s12665-021-09740-1

Azizi, A. H., & Lane, S. N. (2025). Impacts and downstream propagation of glacial lake outburst floods (GLOFs) in Afghanistan: A case study of the 2018 and 2021 outbursts in Peshghor, Panjshir Valley. In *International Mountain Conference 2025 (IMC25)*.

Azizi, A. H., Akhtar, F., Tischbein, B., Borgemeister, C., & Wang, Q. (2024). Assessing long-term water storage dynamics in Afghanistan: An integrated approach using machine learning, hydrological models, and remote sensing. *Journal of Environmental Management*, *370*, 122901. https://doi.org/10.1016/j.jenvman.2024.122901

Azizi, A. H., et al. (2025). Glacial lake formation and evolution in the Hindukush Region of Afghanistan between 1990 and 2020. *Geografiska Annaler: Series A, Physical Geography*. Advance online publication. https://doi.org/10.1080/04353676.2025.2554438

Bajracharya, S. R., et al. (2020). *Inventory of glacial lakes and identification of potentially dangerous glacial lakes in the Koshi, Gandaki, and Karnali river basins of Nepal, the Tibet Autonomous Region of China*. ICIMOD. https://doi.org/10.53055/icimod.773

Benn, D. I., Bolch, T., Hands, K., Gulley, J., Luckman, A., Nicholson, L. L., Quincey, D., Thompson, S., Toumi, R., & Wiseman, S. (2012). Response of debris-covered glaciers in the Mount Everest region to recent warming, and implications for outburst flood hazards. *Earth-Science Reviews*, *114*(1–2), 156–174.

Bjelica, J. (2021). *Shrinking, thinning, retreating: Afghan glaciers under threat from climate change*. Afghanistan Analysts Network. https://www.afghanistan-analysts.org

Bolch, T., et al. (2011). Identification of potentially dangerous glacial lakes in the northern Tien Shan. *Natural Hazards*, *59*, 1691–1714. https://doi.org/10.1007/s11069-011-9860-2

Buchroithner, M. F., & Bolch, T. (2014). Glacier lake outburst floods (GLOFs)—Mapping the hazard of a threat to High Asia and beyond. In *Impact of global changes on mountains: Responses and adaptation* (pp. 324–345). CRC Press. https://doi.org/10.1201/b17963-21

Cao, X. C., Liu, Z. Z., & Li, W. S. (2016). Glacial lake mapping and analysis of the potentially dangerous glacial lakes before Nepal 4·25 earthquake in 2015. *Journal of Glaciology and Geocryology*, *38*(3), 573–583.

Carrivick, J. L., & Tweed, F. S. (2013). Proglacial lakes: Character, behaviour and geological importance. *Quaternary Science Reviews*, *78*, 34–52. https://doi.org/10.1016/j.quascirev.2013.07.028

CBS News. (2018, July 16). *Dam burst in Afghanistan's Panjshir Valley floods villages and kills at least 10*. https://www.cbsnews.com

Chapman, K. (2024). *Climate zones of Afghanistan*. Earth Site Education. https://www.earth-site.co.uk/Education/climate-zones-of-afghanistan-different-climate-regions-of-afghanistan/

Chowdhury, A., De, S. K., Sharma, M. C., & Debnath, M. (2022). Potential glacial lake outburst flood assessment in a changing environment, Chhombo Chhu watershed, Sikkim Himalaya, India. *Geocarto International, 37*(27), 15627–15655. https://doi.org/10.1080/10106049.2022.2102219

Cook, K. L., Andermann, C., Gimbert, F., Adhikari, B. R., & Hovius, N. (2018). Glacial lake outburst floods as drivers of fluvial erosion in the Himalaya. *Science, 362*(6410), 53–57. https://doi.org/10.1126/science.aat4981

Cook, S. J., & Swift, D. A. (2012). Subglacial basins: Their origin and importance in glacial systems and landscapes. *Earth-Science Reviews, 115*(4), 332–372. https://doi.org/10.1016/j.earscirev.2012.09.009

Das, S., Das, S., Mandal, S. T., Sharma, M. C., & Ramsankaran, R. (2024). Inventory and GLOF susceptibility of glacial lakes in Chenab basin, Western Himalaya. *Geomatics, Natural Hazards and Risk, 15*(1), 2356216. https://doi.org/10.1080/19475705.2024.2356216

Emmer, A. (2017). Glacier retreat and glacial lake outburst floods (GLOFs). In *Oxford research encyclopedia of Natural Hazard Science*. Oxford University Press. https://doi.org/10.1093/acrefore/9780199389407.013.275

Emmer, A., & Cochachin, A. (2013). The causes and mechanisms of moraine-dammed lake failures in the Cordillera Blanca, North American Cordillera, and Himalayas. *AUC Geographica, 48*(2), 5–15. https://doi.org/10.14712/23361980.2014.23

Emmer, A., Klimeš, J., Mergili, M., Vilímek, V., & Cochachin, A. (2016). 882 lakes of the Cordillera Blanca: An inventory, classification, evolution and assessment of susceptibility to outburst floods. *Catena, 147*, 269–279. https://doi.org/10.1016/j.catena.2016.07.032

Emmer, A., et al. (2022). Progress and challenges in glacial lake outburst flood research (2017–2021): A research community perspective. *Natural Hazards and Earth System Sciences Discussions, 2022*, 1–34. https://doi.org/10.5194/nhess-2022-143

EUAA. (2020). *Afghanistan: Country focus – Panjshir*. European Union Agency for Asylum. https://euaa.europa.eu

Farahmand, A., Hussaini, M. S., Jawadi, H. A., Abrunhosa, M., & Thomas, B. F. (2023). Multi-criteria decision process to identify groundwater potential zones using geospatial tools in the Arghandab river basin, Afghanistan. *Environmental Earth Sciences, 82*(14), 362. https://doi.org/10.1007/s12665-023-11046-3

Field, H. R., Armstrong, W. H., & Huss, M. (2021). Gulf of Alaska ice-marginal lake area change over the Landsat record and potential physical controls. *The Cryosphere, 15*(7), 3255–

3278. https://doi.org/10.5194/tc-15-3255-2021

Fischer, M., Korup, O., Veh, G., & Walz, A. (2021). Controls of outbursts of moraine-dammed lakes in the greater Himalayan region. *The Cryosphere*, *15*(8), 4145–4163. https://doi.org/10.5194/tc-15-4145-2021

Fujita, K., Sakai, A., Nuimura, T., Yamaguchi, S., & Sharma, R. R. (2013). Recent changes in Imja Glacial Lake and its damming moraine in the Nepal Himalaya revealed by in situ surveys and multi-temporal ASTER imagery. *Natural Hazards and Earth System Sciences*, *13*(10), 255–592.

Gardelle, J., Arnaud, Y., & Berthier, E. (2011). Contrasted evolution of glacial lakes along the Hindu Kush Himalaya mountain range between 1990 and 2009. *Global and Planetary Change*, *75*(1–2), 47–55. https://doi.org/10.1016/j.gloplacha.2010.10.003

Gouli, M. R., Hu, K., Khadka, N., & Talchabhadel, R. (2023). Hazard assessment of a pair of glacial lakes in Nepal Himalaya: Unfolding combined outbursts of upper and lower Barun. *Geomatics, Natural Hazards and Risk*, *14*(1), 2266219. https://doi.org/10.1080/19475705.2023.2266219

Haeberli, W., et al. (2016). New lakes in deglaciating high-mountain regions: Opportunities and risks. *Climatic Change*, *139*, 201–214. https://doi.org/10.1007/s10584-016-1771-5

Haritashya, U. K., et al. (2018). Evolution and controls of large glacial lakes in the Nepal Himalaya. *Remote Sensing*, *10*(5), 798. https://doi.org/10.3390/rs10050798

Harrison, S., et al. (2018). Climate change and the global pattern of moraine-dammed glacial lake outburst floods. *The Cryosphere*, *12*(4), 1195–1209. https://doi.org/10.5194/tc-12-1195-2018

Hu, J., et al. (2022). Temporal and spatial changes and GLOF susceptibility assessment of glacial lakes in Nepal from 2000 to 2020. *Remote Sensing*, *14*(19), 5034. https://doi.org/10.3390/rs14195034

Huggel, C., Kääb, A., Haeberli, W., Teysseire, P., & Paul, F. (2002). Remote sensing-based assessment of hazards from glacier lake outbursts: A case study in the Swiss Alps. *Canadian Geotechnical Journal*, *39*(2), 316–330. https://doi.org/10.1139/t01-099

Huggel, C., Haeberli, W., Kääb, A., Bieri, D., & Richardson, S. (2004). An assessment procedure for glacial hazards in the Swiss Alps. *Canadian Geotechnical Journal*, *41*(6), 1068–1083. https://doi.org/10.1139/t04-053

ICIMOD. (2011). *Glacial lakes and glacial lake outburst floods in Nepal*. International Centre for Integrated Mountain Development.

ICIMOD. (2019). *Glacial lake outburst floods: Addressing the threat to communities in Afghanistan*. International Centre for Integrated Mountain Development.

ICIMOD. (2024). *GLOF database of High Mountain Asia* [Dataset]. International Centre for Integrated Mountain Development. https://doi.org/10.26066/RDS.1973283

IPCC. (2021). *Climate change 2021: The physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.

Iribarren Anacona, P., Norton, K. P., & Mackintosh, A. (2014). Moraine-dammed lake failures in Patagonia and assessment of outburst susceptibility in the Baker Basin. *Natural Hazards and Earth System Sciences, 14*(12), 3243–3254. https://doi.org/10.5194/nhess-14-3243-2014

Islam, N., & Patel, P. P. (2022). Inventory and GLOF hazard assessment of glacial lakes in the Sikkim Himalayas, India. *Geocarto International, 37*(13), 3840–3876. https://doi.org/10.1080/10106049.2020.1869332

Ives, J. D., Shrestha, R. B., & Mool, P. K. (2010). *Formation of glacial lakes in the Hindu Kush–Himalayas and GLOF risk assessment*. ICIMOD. https://doi.org/10.53055/icimod.521

Jiang, S., et al. (2018). Glacier change, supraglacial debris expansion and glacial lake evolution in the Gyirong River basin, central Himalayas, between 1988 and 2015. *Remote Sensing, 10*(7), 986. https://doi.org/10.3390/rs10070986

Kamp, U., Byrne, M., & Bolch, T. (2011). Glacier fluctuations between 1975 and 2008 in the Greater Himalaya Range of Zanskar, southern Ladakh. *Journal of Mountain Science, 8*, 374–389. https://doi.org/10.1007/s11629-011-2007-9

Khadka, N., Zhang, G., & Thakuri, S. (2018). Glacial lakes in the Nepal Himalaya: Inventory and decadal dynamics (1977–2017). *Remote Sensing, 10*, 1913. https://doi.org/10.3390/rs10121913

Khadka, N., et al. (2021). Evaluation of glacial lake outburst flood susceptibility using multi-criteria assessment framework in Mahalangur Himalaya. *Frontiers in Earth Science, 8*, 601288. https://doi.org/10.3389/feart.2020.601288

Khanal, N. R., Shrestha, A. B., & Shrestha, R. (2015). *Preparing for floods: Experience from Nepal*. International Centre for Integrated Mountain Development. https://doi.org/10.13140/RG.2.1.2925.4560

King, O., Bhattacharya, A., Bhambri, R., & Bolch, T. (2019). Glacial lakes exacerbate Himalayan glacier mass loss. *Scientific Reports, 9*, 18145. https://doi.org/10.1038/s41598-019-53733-x

Konrad, S. K., & Clark, D. H. (1998). Evidence for an early Neoglacial glacier advance from rock glaciers and lake sediments in the Sierra Nevada, California, USA. *Arctic and Alpine Research, 30*(3), 272–284. https://doi.org/10.2307/1551975

Kougkoulos, I., et al. (2018). Use of multi-criteria decision analysis to identify potentially dangerous glacial lakes. *Science of the Total Environment, 621*, 1453–1466. https://doi.org/10.1016/j.scitotenv.2017.10.083

Leitzell, K. (2013, May 28). *Glacial lake outburst floods threaten millions globally*. National Snow and Ice Data Center. https://nsidc.org

MAIL. (2020). *Digital elevation model (DEM) of Afghanistan*. Ministry of Agriculture, Irrigation and Livestock, Kabul.

Maharjan, S. B., et al. (2021a). Monitoring of glaciers and glacial lakes in Afghanistan. In S. Bajracharya & B. Shrestha (Eds.), *Earth observation science and applications for risk reduction and enhanced resilience in Hindu Kush Himalaya Region: A decade of experience from SERVIR* (pp. 211–230). Springer. https://doi.org/10.1007/978-3-030-73569-2_11

Maharjan, S. B., et al. (2021b). *Glaciers in Afghanistan: Status and changes from 1990 to 2015*. ICIMOD. https://doi.org/10.53055/icimod.784

Ministry of Energy and Water (MEW). (2022). *Hydro-meteorological data*. MEW, Kabul.

Ministry of Mines and Petroleum (MoMP). (2020). *High-resolution RGB imagery and geological data of Afghanistan*. MoMP, Kabul.

Mool, P. K., et al. (2011). *Glacial lakes and glacial lake outburst floods in Nepal*. ICIMOD.

Muneeb, F., Baig, S. U., Khan, J. A., & Khokhar, M. F. (2021). Inventory and GLOF susceptibility of glacial lakes in Hunza River basin, western Karakoram. *Remote Sensing, 13*(9), 1794. https://doi.org/10.3390/rs13091794

Prakash, C., & Nagarajan, R. (2018). Glacial lake changes and outburst flood hazard in Chandra basin, north-western Indian Himalaya. *Geomatics, Natural Hazards and Risk, 9*(1), 337–355. https://doi.org/10.1080/19475705.2018.1445663

Richardson, S. D., & Reynolds, J. M. (2000). An overview of glacial hazards in the Himalayas. *Quaternary International, 65–66*, 31–47. https://doi.org/10.1016/S1040-6182(99)00035-X

Rick, B., McGrath, D., Armstrong, W., & McCoy, S. W. (2022). Dam type and lake location characterize ice-marginal lake area change in Alaska and NW Canada between 1984 and 2019. *The Cryosphere, 16*(1), 297–314. https://doi.org/10.5194/tc-16-297-2022

Rinzin, S., Zhang, G., & Wangchuk, S. (2021). Glacial lake area changes and potential outburst flood hazard assessment in the Bhutan Himalaya. *Frontiers in Earth Science, 9*, 775195. https://doi.org/10.3389/feart.2021.775195

Rounce, D. R., McKinney, D. C., Lala, J. M., Byers, A. C., & Watson, C. S. (2016). A new remote hazard and risk assessment framework for glacial lakes in the Nepal Himalaya. *Hydrology and Earth System Sciences, 20*(9), 3455–3475. https://doi.org/10.5194/hess-20-3455-2016

Saaty, T. L. (1990). An exposition of the analytic hierarchy process. *Management Science, 36*(3), 259–268. https://doi.org/10.1287/mnsc.36.3.259

Saaty, T. L. (2008). Decision making with the analytic hierarchy process. *International Journal* *of Services Sciences, 1*(1), 83–98. https://doi.org/10.1504/IJSSCI.2008.017590

Saaty, T. L., & Vargas, L. G. (2012). The possibility of group choice: Pairwise comparisons and merging functions. *Social Choice and Welfare, 38*(3), 481–496. https://doi.org/10.1007/s00355-011-0541-6

Sattar, A., et al. (2021). Future glacial lake outburst flood (GLOF) hazard of the South Lhonak Lake, Sikkim Himalaya. *Geomorphology, 388*, 107783. https://doi.org/10.1016/j.geomorph.2021.107783

Sattar, A., Allen, S., Mergili, M., Haeberli, W., Frey, H., Kulkarni, A. V., Haritashya, U. K., Huggel, C., Goswami, A., & Ramsankaran, R. A. A. J. (2023). Modeling potential glacial lake outburst flood process chains and effects from artificial lake-level lowering at Gepang Gath Lake, Indian Himalaya. *Journal of Geophysical Research: Earth Surface, 128*(3), e2022JF006826. https://doi.org/10.1029/2022JF006826

Schaub, Y., Huggel, C., & Cochachin, A. (2016). Ice-avalanche scenario elaboration and uncertainty propagation in numerical simulation of rock-/ice-avalanche-induced impact waves at Mount Hualcán and Lake 513, Peru. *Landslides, 13*, 1445–1459. https://doi.org/10.1007/s10346-015-0658-2

SERVIR. (2019). *Glacial lake outburst floods: Addressing the threat to communities in Afghanistan*. SERVIR Hindu Kush Himalaya / ICIMOD.

Shokory, J. A., & Lane, S. N. (2024). Ice cover loss and debris cover evolution in the Afghanistan Hindu Kush Himalaya between 2000 and 2020. *Arctic, Antarctic, and Alpine Research, 56*(1), 2373858. https://doi.org/10.1080/15230430.2024.2373858

Shrestha, A. B., et al. (2021). Developing a science-based policy network over the Upper Indus Basin. *Science of the Total Environment, 784*, 147067. https://doi.org/10.1016/j.scitotenv.2021.147067

Shrestha, F., et al. (2023). A comprehensive and version-controlled database of glacial lake outburst floods in High Mountain Asia. *Earth System Science Data, 15*(9), 3941–3961. https://doi.org/10.5194/essd-15-3941-2023

Shroder, J. F., & Weihs, B. J. (2010). Geomorphology of the Lake Shewa landslide dam, Badakhshan, Afghanistan, using remote sensing data. *Geografiska Annaler: Series A, Physical Geography, 92*(4), 469–483. https://doi.org/10.1111/j.1468-0459.2010.00408.x

Song, C., Sheng, Y., Ke, L., Nie, Y., & Wang, J. (2016). Glacial lake evolution in the southeastern Tibetan Plateau and the cause of rapid expansion of proglacial lakes linked to glacial–hydrogeomorphic processes. *Journal of Hydrology, 540*, 504–514. https://doi.org/10.1016/j.jhydrol.2016.06.054

Taylor, C., Robinson, T. R., Dunning, S., Carr, J. R., & Westoby, M. (2023). Glacial lake outburst floods threaten millions globally. *Nature Communications, 14*(1), 36033. https://doi.org/10.1038/s41467-023-36033-x

ThermMedia. (2025, June 14). Devastating flood in Baghlan: Five villages destroyed. *Varient—News Magazine*. https://thermmedia.com/devastating-flood-in-baghlan-five-villages-destroyed

TOLO News. (2018, July 13). 10 people killed in deadly chain of disasters in Panjshir. https://tolonews.com/afghanistan/10-people-killed-deadly-chain-disasters-panjshir

UNESCO. (2025). *Glaciers and mountains: Melting water towers will aggravate global crises (World Water Development Report 2025)*. UNESCO. https://www.unesco.org/en/articles/glaciers-and-mountains-melting-water-towers-will-aggravate-global-crises-report

United Nations. (2012). *Glacial Lake Outburst Flood (GLOF): Reducing risks and ensuring preparedness. Report on the International Conference*. United Nations.

Veettil, B. K., & Kamp, U. (2019). Global disappearance of tropical mountain glaciers: Observations, causes, and challenges. *Geosciences, 9*(5), 196. https://doi.org/10.3390/geosciences9050196

Wang, W., Yao, T., Gao, Y., Yang, X., & Kattel, D. B. (2011). A first-order method to identify potentially dangerous glacial lakes in a region of the southeastern Tibetan Plateau. *Mountain Research and Development, 31*(2), 122–130. https://doi.org/10.1659/MRD-JOURNAL-D-10-00059.1

Wang, W., Xiang, Y., Gao, Y., Lu, A., & Yao, T. (2015). Rapid expansion of glacial lakes caused by climate and glacier retreat in the central Himalayas. *Hydrological Processes, 29*(6), 859–874. https://doi.org/10.1002/hyp.10199

Wang, X., et al. (2013). Changes of glacial lakes and implications in Tian Shan, Central Asia, based on remote sensing data from 1990 to 2010. *Environmental Research Letters, 8*(4), 044052.

World-Data. (2024). *Afghanistan: General information, economy, climate and geography*. https://www.worlddata.info/asia/afghanistan/

WRD. (2018). *A report on the causes and failure manner of the glacial lake outburst flood in Panjshir: Field-based report*. Water Resources Directorate, Ministry of Energy and Water, Kabul, Afghanistan.

Xinhua Net. (2018, July 12). At least 10 killed as dike of lake bursts in eastern Afghanistan. *Xinhua News*. http://www.xinhuanet.com/english/2018-7/12/c_137319261.htm

Yang, L., Lu, Z., Zhao, C., Kim, J., Yang, C., Wang, B., Liu, X., & Wang, Z. (2022). Analyzing the triggering factors of glacial lake outburst floods with SAR and optical images: A case study in Jinweng Co, Tibet, China. *Landslides, 19*(4), 855–864.

Yao, X., Liu, S., Han, L., Sun, M., & Zhao, L. (2018). Definition and classification system of glacial lake for inventory and hazards study. *Journal of Geographical Sciences, 28*(2), 193–205. https://doi.org/10.1007/s11442-018-1467-z

Zhang, G., Yao, T., Xie, H., Wang, W., & Yang, W. (2015). An inventory of glacial lakes in the Third Pole region and their changes in response to global warming. *Global and Planetary Change, 131*, 148–157. https://doi.org/10.1016/j.gloplacha.2015.05.013

Zhang, M., Chen, F., Zhao, H., Wang, J., & Wang, N. (2021). Recent changes of glacial lakes in High Mountain Asia and potential controlling factors analysis. *Remote Sensing*, *13*(18), 3757. https://doi.org/10.3390/rs13183757

Zhang, T., Wang, W., An, B., Gao, T., & Yao, T. (2022). Ice thickness and morphological analysis reveal the future glacial lake distribution and formation probability in the Tibetan Plateau and its surroundings. *Global and Planetary Change, 216*, 103923. https://doi.org/10.1016/j.gloplacha.2022.103923