Contents lists available at ScienceDirect

Heliyon



journal homepage: www.cell.com/heliyon

Research article

5²CelPress

Assessing climate-driven impacts on Karakoram glacier surge: A geospatial analysis highlighting Shishper Glacial Lake outburst flood events (2019–2022) as prime example

Mehtabidah Ali

Department of Earth and Atmospheric Sciences, Natural Sciences and Mathematics, University of Houston, Houston, TX, 77204, USA

ARTICLE INFO

Keywords: Shishper glacier Karakorum range Remote sensing Geographic information system (GIS) Modified normalized water index (MNDWI) Water peak discharge Landsat-08 GLOF Surging Ravine Water discharge

ABSTRACT

The Northern Areas of Pakistan encompass the Hindukush, Karakoram, and Himalayan mountain ranges witnessing glacier surging, exacerbated by climate warming. As glaciers rapidly melt, ravines experience heightened blockage and migration, obstructing stream discharges and forming expansive ice-dammed lakes. The rupture of these natural dams triggers Glacial Lake Outburst Floods downstream in the primary glacier's ravine. The catastrophic Glacial Lake Outburst Floods in 2022 across the Karakoram ranges in Northern Pakistan prompted this study. It focuses on Shishper Glacier Lake. The aim is to provide complete flood observations and their devastating effects on downstream communities. Analysis of Landsat 08 Imagery reveals the evolution of Shishper Glacier Lake from its initiation in November 2018 to the catastrophic GLOF in May 2022. The lake reached a maximum area of 0.32 km² in 2019 and its successive breaches on June 22, 2019, and May 29, 2020, reduced it to 0.018 km². Draining continued until July 2021, shrinking the lake area to 0.009 km². A noteworthy 2.73 °C temperature increase in 2022 correlated with an expansion of the lake area to 0.33 km², culminating in the GLOF on May 7th, 2022. The study emphasizes the critical need for mapping, assessing, and monitoring surging glaciers and glacier-formed lakes in the Karakoram ranges to safeguard downstream communities from potential hazards.

1. Introduction

Glacial Lake Outburst Floods (GLOFs) have emerged as a significant phenomenon in Northern Pakistan's Karakoram, Himalayan, and Hindukush (HKH) mountain ranges. The accelerated melting of glaciers, driven by rising temperatures has led to the formation of 3,044 glacial lakes in the region from 2001 to 2013 [1]. This poses a considerable threat to downstream communities, as glacier lake outbursts are inherently hazardous. An assessment indicates that 33 glacial lakes are susceptible to potentially catastrophic GLOFs, putting over 7.1 million people in the region at risk [2].

Glacial Lake Outburst Floods represent high-magnitude, low-frequency events characterized by substantial geomorphic consequences, extreme hydrological features, and the potential for adverse impacts on downstream communities [3]. The primary triggers for GLOFs involve snowmelt that influences mechanisms such as overflow, subsurface channel opening, dam destabilization, and moraine collapse [4]. The interplay of snowmelt contributes to the enlargement of glacier-trapped lakes, resulting in elevated hydrostatic pressure which, when breached, leads to subsequent downstream flooding events [5].

Received 13 March 2024; Received in revised form 25 June 2024; Accepted 6 August 2024

Available online 8 August 2024

E-mail address: mali50@cougarnet.uh.edu.

https://doi.org/10.1016/j.heliyon.2024.e35951

^{2405-8440/© 2024} The Author. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

Globally, the Hindu Kush, Himalayan, and Karakoram ranges emerge as a region particularly susceptible to GLOFs [6]. The dynamic climatic conditions in this region contribute to the reduction of snow masses, glacier surges, and the expansion of glacial lakes [7]. These environmental changes in the HKH range heighten the risk of GLOFs, emphasizing the urgent need for research and mitigation strategies to address the potential hazards associated with these phenomena [8].

Surge events in the HKH have been documented since the early 19th century. Initially perceived as unexpected occurrences linked to avalanches and seismic activity on the Karakoram ranges, these surging glaciers were initially believed to be unrelated to climate trends [9]. Later, the first widespread survey, relying on satellite imagery, confirmed the existence of surge-type glaciers and initiated discussions surrounding their characteristics. The Karakoram mountain ranges exhibit the highest concentrations of surge-type glaciers globally, characterized by irregular ice movements. It hosts 90 surge-type glaciers, with an additional 10 surge-type glaciers recently identified [10].

As observed by Kapitsa et al. [11], glacial dynamics in the HKH ranges exhibit a notable phenomenon, where surging glaciers undergo accelerated flow, impeding the natural course of streams and rivers originating from retreating glacial formations. This process results in the formation of new glacial lakes, as articulated by Round et al. [12]. A pertinent example of this occurrence is explained in the case of the Shishper Glacier within the Karakoram range. Commencing its accelerated flow in April 2018, the glacier swiftly blocked a ravine and cut off the outlet stream originating from the adjacent receding Muchawar glacier, as detailed by Rashid et al. [13]. The meeting point, where the surging Shishper glacier intercepted the ravine and blocked the river from the Muchawar glacier, became a reservoir, evolving into the Shishper glacial lake by November 2018. This transformation posed a significant threat to GLOFS in the Hassanabad region [14]. The scientific scrutiny of the Shishper Glacier intensified when it manifested the potential for catastrophic consequences in downstream communities a concern. The accelerated velocity of the Shishper glacier induced an increased tendency to obstruct ravines beyond historical patterns, leading to the impediment of stream discharge emanating from the adjacent ravine. Subsequently, the rupture of glacial damming gives rise to catastrophic flooding downstream within the primary glacier's ravine [15].

Generally, Glacial lakes respond to climate change primarily through formation and expansion as glaciers melt at accelerated rates, filling depressions with meltwater and creating new lakes or enlarging existing ones. The increased meltwater input alters their volume and depth, often resulting in deeper and larger lakes. Rising temperatures warm the lake water, impacting aquatic ecosystems and altering the chemical composition with higher sediment and nutrient levels [16]. This warming trend also heightens the risk of Glacial Lake Outburst Floods (GLOFs), where natural dams of ice or moraine can fail, causing catastrophic downstream flooding. The changing water temperature and chemistry disrupt local biodiversity, favoring different species and altering ecosystem dynamics. Sedimentation increases turbidity, affecting aquatic life and potentially reducing the lake's lifespan by filling the basin more rapidly [17]. These changes are evident in regions like the Himalayas, Andes, and Alps, where significant glacial lake growth poses risks and challenges for water resource management [15].

The intersection of mountain glaciations and climate fluctuations stands as a prominent concern within the field of geosciences [18]; [19]. Despite this, the phenomenon of glaciers surging in the Hindu Kush Himalaya ranges in Northern Pakistan has been relatively overlooked by researchers [20]. The scarcity of data on HKH glacier melting and lake formation is attributed to the



74°30'0"E 74°31'30"E 74°33'0"E 74°34'30"E 74°36'0"E 74°37'30"E 74°39'0"E 74°40'30"E 74°42'0"E 74°43'30"E 74°45'0"

Fig. 1. Location map of Shishper Glacial Lake in Hassanabad, Western Karakoram. True color Landsat-8 OLI image captured on May 5th, 2022.

challenging accessibility and harsh weather conditions prevalent in the region [4]. Furthermore, predicting Glacial Lake Outburst Floods in HKH mountainous terrains poses challenges due to the intricate outburst mechanisms and longitudinal profiles of steep mountain valleys [21]. In addressing these challenges, Remote Sensing (RS) and Geographic Information Systems (GIS) emerge as essential tools for the early detection and continuous monitoring of glacial lakes in the HKH ranges [22]. The accurate delineation of glacial lake boundaries on remote sensing imagery is a pivotal step in predicting the GLOFs and their associated hazards [23].

Understanding the dynamics of glacier response and glacial lake formation is crucial from an early stage. This understanding lays the groundwork for potential planning and engineering interventions aimed at mitigating GLOF hazards and regulating water outflow from these lakes. Additionally, studies on glacial lakes play a crucial role in enhancing disaster resilience [24].

Identification of potential risks associated with GLOFs, and the development of mitigation strategies are necessary. Therefore, continuous assessment and monitoring of individual glacial lakes are essential to protect downstream communities in the Karakoram ranges of Northern Pakistan. This research's primary objective is to observe Glacial Lake Outburst Floods in the Karakoram ranges while taking Shishper GLOF events (2019–2022) as a prime example.

1.1. Study area

Shishper Glacier extending over a length of 16.5 km is situated on the Karakoram range more specifically in the Hunza River Raven (Nallah) within the confines of Gilgit-Baltistan, Northern Pakistan (See Fig. 1). The downstream area of Shishper Glacier is Hassanabad village and it encompasses 23 glaciers, spanning an area of 88 km² [25]. Most studies have identified two principal glaciers in the Hassanabad region: Shishper Glacier and Muchawar Glacier (see Fig. 1) [26]. Shishper Glacier encompasses an area of 54.7 km², with an elevation range spanning 7611 m above sea level. This glacier relies on winter snow accumulation from peaks at approximately 7700 m–7000 m for sustenance. The combined watershed area of the Shishper and Muchawar glaciers is determined to be 359 km² [27]. The Shishper glacier region experiences an annual precipitation of 125 mm and maintains an average temperature of 11 °C [14].

Notably, Hassanabad village faces susceptibility to Glacial Lake Outburst Floods due to the dynamic movement of the Shishper Glacier, impeding the outlet water flow from the neighboring Muchawar glacier [28]. Positioned 5 km downstream from the Shishper Glacier snout, Hassanabad village is not the sole entity at risk; downstream communities, the Karakoram Highway (KKH) connecting Pakistan with China, residential areas, a 1200-Kilowatt electricity-generating hydroelectric power plant, and the concrete bridge linking Pakistan and China are all exposed to potential GLOF events originating from the Shishper Glacier [13].

2. Methodology

2.1. Data source and data acquisition

Landsat 08 OLI imagery served as the primary data source for the observation of the Shishper Glacial Lake. Image datasets covering distinct periods, namely October 2019, July 2020, June 2021, and May 2022, were obtained from the United States Geological Survey Earth Explorer Interface (USGS). A total of 55 Landsat 08 OLI, level 1 Tier images were downloaded for subsequent analysis. The processing of Landsat 08 OLI products involved minimal geometric corrections, given the orthorectified nature of the data. Due to the dominant challenge of cloud cover in the Karakoram Range, efforts were made to obtain images with minimal cloud cover, ensuring that cloud cover remained below 10 %.

2.1.1. Sensor and image selection

The preference for Landsat 08 OLI imagery over Sentinel-2 was grounded in Landsat's broader coverage capacity, encompassing a larger geographical area. Landsat 08 is equipped with an OLI sensor, features a swath width of 185 km and a temporal resolution of 16 days. This choice aligned with the study's objectives, requiring temporally consistent coverage of Shishper Glacial Lake and its surroundings in the Karakoram region.

2.2. Data processing

The methodology for data processing in this study was accomplished systematically, involving a series of essential steps. Initially, a mask was created to conceal pixels with any band displayed zero or non-values. Following this, radiometric calibration for radiance was applied to the Landsat 8 OLI data, a crucial step that enabled precise quantitative measurements. Subsequently, the Quick Atmospheric Correction algorithm (QUAC) was employed to convert the radiometrically calibrated Landsat 08 OLI data to reflectance. This conversion considered the mask created in the initial step, ensuring the integrity of the reflectance data. Finally, a Band Math Expression was utilized to rescale the reflectance data, normalizing values within the range of -1 to 1. This processing workflow aimed to enhance the quality and comparability of the data, providing a strong foundation for the subsequent mapping and assessment of glacial lake outburst floods in the Karakoram Range.

2.3. Ice-dammed lake identification and mapping

The Modified Normalized Difference Water Index (MNDWI) serves as a widely employed spectral index in remote sensing applications, particularly for the identification of water bodies in satellite imagery [29,30]. In this study, the Modified Normalized Difference Water Index (MNDWI) technique was applied to facilitate the identification of Shishper Glacial Lake, aiming to comprehend its distinctive features and dynamic behaviors. This technique utilized 30-m resolution data from Landsat 8 OLI bands, including band 3 (Green; 0.53–0.59 µm), and band 5 Near Infrared (NIR; 0.85–0.88 µm).

The equation for MNDWI is expressed as follows:

$$MNDWI = \frac{Green - NIR}{Green + NIR}$$

Green represents the reflectance in the green band of the electromagnetic spectrum, and NIR stands for Near Infrared reflectance. The MNDWI formula calculates the normalized difference between the green and near-infrared bands, providing a quantitative measure of water content within the observed area.

2.4. Extraction of lake boundary and area

The extraction of Shishper Glacial Lake's boundary and area employed a systematic methodology, integrating remote sensing techniques and Geographic Information Systems (GIS). High-resolution satellite imagery, specifically sourced from the Landsat-08 OLI dataset was pre-processed, involving radiometric and geometric corrections to enhance data accuracy. Subsequently, the Modified Normalized Difference Water Index and thresholding techniques were applied to distinguish water pixels from other land covers, resulting in a binary image highlighting water pixels. GIS software was instrumental in calculating the lake's area based on the extracted boundary, considering the spatial resolution of the imagery for accurate measurements. Finally, maps were generated through GIS tools, visually presenting the extracted lake boundary and associated lake area, providing clear representations of Shishper Glacial Lake features for effective visualization.

2.5. Estimation of Shishper Glacial Lake volume

The determination of glacier lake volume holds significant importance in the study of Glacier Lake Outburst Floods. The determination of Shishper Glacial Lake volume is conducted through the application of a methodology offered by [31]. The volume (V) is computed using the formula:

$$V = 0.035 \times \widehat{A}1.5$$

where V represents the volume in cubic kilometers (km³), and A denotes the area of the glacial lake in square kilometers (km²).

Due to the impracticality of obtaining direct physical measurements of the lake area due to inaccessibility, the study relied on the Modified Normalized Difference Water Index values derived from Landsat 8 OLI imagery. This prescribed method, has demonstrated efficacy and has undergone successful validation for volume estimation of various glacial lakes within the Hindu Kush Himalayan Karakoram ranges [13,14,26]. This validation is also evidenced by the results obtained in studies conducted by Roberts [32], and Westoby et al. [5] confirming the reliability and applicability of the method beyond its original proposal. (Rebuttal in PDF).

2.6. Shishper GLOF water discharge peaks

The assessment of Shishper Glacier Lake Outburst Floods involves a thorough analysis of peak discharges during significant GLOF events in 2019, 2020, and 2022. The Aga Khan Agency for Habitat (AKAH), a nonprofit organization within the Aga Khan Development Network (AKDN), obtained peak water discharge data while following the methodology of Rafiq et al. (2019) [33]. AKAH utilized a combination of field measurements and hydrological modeling to estimate peak discharges. The methodology involved several key steps: conducted field surveys to collect data on lake geometry, including depth, surface area, and volume, used Digital Elevation Models (DEMs) to analyze the topography and identify potential outburst paths, and applied the empirical formula below,

$$Qpeak = 0.1 * V^{0.67}$$

where Q_{peak} is the peak discharge in cubic meters per second (m³/s) and V is the lake volume in cubic meters (m³). Hydrodynamic models like HEC-RAS were also used to simulate water flow and estimate peak discharge more accurately. Measurements were conducted at the main bridge in Hassanabad, and the water discharge equation was employed to quantify the discharge. The obtained water discharge data for Shishper Glacier in the years 2019, 2020, and 2022, sourced from AKAH Pakistan provides essential information for GLOF simulations such as depth, time of breach, surface area and volume. This contributes to understand the hydrodynamic behavior of this glacial lake system (see Table 2).

3. Results and discussion

3.1. Modified normalized difference water index (MNDWI)

Modified Normalized Difference Water Index (MNDWI) pixel values confirmed water and non-water bodies. Water bodies exhibited positive pixel values greater than zero, consistent with the principle that water absorbs more near-infrared light. Concurrently, vegetation, glaciers, barren rocks, and soil displayed negative values (see Fig. 2 a, b, c & d). Notably, the imagery illustrated a light green tone associated with the Shishper, Muchawar, and other glaciers, a sea green tone represented vegetation, a dark brown tone

showed barren rocks & soil, light pink represented snow, and a dark blue tone represented water bodies on Mount Shishper. This contrast was particularly pronounced in the MNDWI images. The Shishper glacial lake and water sourced from adjacent melting glaciers emerged with an evident dark blue hue (see Fig. 2 a, b, c & d).

The negative values associated with the features in the MNDWI images played a crucial role in the delineation process. By suppressing and removing these negative values, the MNDWI effectively eliminated the spectral influence of vegetation and barren terrain. Consequently, the MNDWI images became a powerful tool for mapping Shishper Glacial Lake distinctly standing out against other features and contributing significantly to the precision and clarity of the mapping, monitoring, and assessment process. The findings of Xu [29] also supported the results of this study. The MNDWI index brings increased positive values for water bodies and decreased values for vegetation, bare rocks, and snow, transitioning from positive to negative values. This dynamic range allows for a more pronounced enhancement of water features in MNDWI images, evidenced contributing to the accurate identification of Shishper Glacial Lake. The application of the MNDWI facilitated the enhanced water-related characteristics.

The study findings highlight the utility of MNDWI in accurately identifying and mapping ice-dammed glacial lakes, providing valuable insights for glaciological studies and hazard assessments in the mountainous region.

3.2. Temporal dynamics and quantification: extracting Shishper Glacial Lake area and volume from October 2018 to May 2022

To comprehend the temporal dynamics associated with the expansion and contraction of the Shishper Glacial Lake, the lake's area was systematically measured during distinct periods: October 2019, July 2020, June 2021, and May 2022. The outcomes of these measurements are depicted in Fig. 2 a, b, c & d. The study observations indicated the absence of a lake before mid-November 2018, a finding confirmed by Landsat 8 OLI imagery captured on October 23rd, 2018, where no visible glacial lake was identified in the region (see supplemental file Fig. 8). This temporal evolution and absence of a lake in the pre-defined period contributed valuable insights into the dynamic nature of Shishper Glacial Lake formation and underscored the significance of ongoing monitoring efforts for glacial lake systems.

The temporal evolution of Shishper Glacial Lake, as observed and analyzed in this study, provides significant insights into its dynamic behavior and the consequences of glacial lake outburst floods on the Karakoram range. Before the initial breach on June 22nd, 2019, the lake's area measured approximately 0.32 km^2 [14]. After the first GLOF event on June 22nd, 2019, the ice-dammed lake experienced a substantial reduction in area, diminishing to $5.67 \times 10^{-2} \text{ km}^2$ by October 10th, 2019 (refer to Table 1). Satellite imagery revealed a renewed expansion, reaching its maximum recorded area of 0.40 km^2 on May 24, 2020 [14]. The second breach transpired on May 29th, 2020, resulting in minor damage to the downstream community [26]. The continuous drainage persisted until July 2020, causing the lake area to contract to 0.018 km^2 by July 24th, 2020 (refer to Table 1). In early August 2021, the outflow from the lake into the Hassanabad ravine ceased might be due to freezing temperatures in the region. Consequently, water began to accumulate within the Shishper Glacial Lake, and as of May 2nd, 2022, the lake covered an area of 0.33 km^2 (see Fig. 2d). The examination of these temporal variations emphasizes the complex relationship between glacial processes, outburst events, and subsequent lake dynamics. These findings contribute to our understanding of the Shishper Glacial Lake's response to climatic conditions and highlight the importance of continued monitoring for effective risk assessment and mitigation strategies in the region.



Fig. 2a. Modified normalized difference water index image capturing the Shishper Glacial Lake on October 10, 2019.



Fig. 2b. Modified normalized difference water index image capturing the Shishper Glacial Lake on July 24, 2020.



Fig. 2c. Modified normalized difference water index image capturing the Shishper Glacial Lake on June 09, 2021.

Furthermore, the lake volume estimated for the years 2019 and 2020, as derived in this study, aligns closely with the estimated volumes of Shishper Glacial Lake reported by [18]. This consistency in volume estimates across different studies provides a level of confidence in the accuracy and reliability of the applied methodology. Notably, the findings of the study reveal that the Shishper Glacial Lake exhibited maximum area on May 2nd, 2022 (see Figs. 2d and 3). A reasonable explanation for this observed peak in lake volume in May 2022 could be linked to the mean monthly temperature trends in the region. Comparing the temperature data, it is evident that the mean monthly temperature increased by 2.73 °C in 2022 compared to historical average temperatures for the last two decades [34]. This temperature rise may have influenced the melting dynamics of the surrounding glaciers, contributing to increased water input and subsequent expansion of the glacial lake. The correlation between temperature variations and lake volume highlights the complex interplay between climatic factors and glacial lake dynamics, underscoring the need for continued monitoring and



Fig. 2d. Modified normalized difference water index image capturing the Shishper Glacial Lake on May 02, 2022.

Table 1				
A clear representation	of the variation in	lake area and	volume over	time.

S. Num	Date	Lake Area (m ²)	Lake Volume (m ³)
1	23rd Oct 2018	No Lake	-
2	10 Oct 2019	0.0567	0.00047
3	24 July 2020	0.018	0.00008
4	09 June 2021	0.009	0.00002
5	02 May 2022	0.33	0.00663

Table 2

Water discharge data during Shishper GLOF events (AKAH Pakistan).

	GLOF Year	Water Discharge $[Q] = (m^3 S^{-1})$
Shishper GLOF Events		
First GLOF	6/22/2019	141.58
Second GLOF	5/29/2020	84.95
Third GLOF	5/07/2022	226.53

detailed climate impact assessments in vulnerable glacial regions of Northern Pakistan.

The elevated area and volume of Shishper Lake during this period contributed to an unprecedented and massive outburst of floodwater. The analysis of Landsat 8 OLI imagery, focused particularly on Shishper glacial lake outburst floods dating back to 2019. The GLOF event that occurred on May 7th, 2022, was catastrophic. The factors influencing this mega-outburst flood can be attributed to the key consideration. The region experienced an increase in temperature in 2022, compared to the mean monthly temperatures of previous years. This temperature rise likely accelerated the surging Shishper Glacier beyond historical rates, potentially contributing to a higher ice mass movement. The increased glacial activity led to the glacier blockage and migrated upstream in the ravine, obstructing the discharge from the side ravine, as visually depicted in (see supplemental file Fig. 7). Consequently, the glacier-induced damming mechanism facilitated the substantial development of a lake in the side ravine. The natural ice dam ultimately ruptured on May 7th, 2022, resulting in an unusually extensive and devastating flood downstream in the ravine of the primary glacier. This analysis emphasizes the complex interaction between climatic variables, glacier dynamics, and the resultant GLOF events, highlighting the importance of ongoing monitoring risk assessment in glacial regions like the Karakoram range.

Secondly, the impact of climate warming on the Shishper Glacial Lake system becomes apparent through the intensified melting of the nearby Muchawar glacier. This observable trend, supported by data from the Pakistan Meteorology Department, indicates a warmer climate in the region, resulting in a more pronounced melting of the Muchawar glacier compared to previous years. The accelerated melting process of the Muchawar glacier has significantly contributed to the augmentation of water inflow into the ice-



Fig. 3. Temporal changes in the area of ice-dammed Shishper glacial lake.

dammed Shishper Lake.

3.3. Shishper GLOFs water discharge peaks

The analysis of peak water discharge data during Glacial Lake Outburst Flood events in 2019, 2020, and 2022 revealed noteworthy insights into the dynamics of these catastrophic events (see Figs. 4–6). Particularly, the GLOF event of May 2022 exhibited the highest downstream flow, as evidenced by the calculated peak water discharge data (see Table 2 & Fig. 6). The drainage pattern indicated subglacial drainage, with accumulated meltwater consistently excavating tunnels through the ice, a phenomenon observed across multiple years. Consistency in peak discharge for the GLOF events of 2019 and 2020 (141.58 & 84.95 m³/s) enhances the robustness of the previous findings [18]. Notably, our field observations revealed a characteristic pattern where water discharge from Shishper Lake exhibited a gradual rise before each GLOF event, reaching a sudden peak at a critical diameter, and triggering the GLOF events (see Figs. 4–6). The discharge peak of the GLOF on May 7th, 2022, stabilized approximately 1 h after its exit from the lake. Furthermore, field observations revealed that (a) the upstream movement of the flood damaged the power station, (b) downstream settlements and orchards were inundated by the GLOF water, and (c) the bridge on the Karakoram Highway (KKH), which connects Pakistan with China, was damaged [35].

4. Conclusion

In conclusion, the temporal evolution analysis of Shishper Glacial Lake has yielded vital insights into the dynamic behavior and responses of the glacial system to climatic conditions in the Karakoram range of Northern Pakistan. The catastrophic GLOF event on May 7th, 2022, served as a reminder of the urgent need for frequent monitoring and extensive risk assessment in glacial regions on the Karakoram range. In addition, this study effectively showed the impact of climate warming on the Shishper Glacial Lake system, emphasizing the understanding of glacial dynamics and climatic factors to mitigate potential risks associated with glacial lake systems. Furthermore, the peak discharges observed during Shishper GLOF events, and the subsequent significant damage to downstream communities during the discharge events, emphasize the need for further research on GLOF responses in the Karakoram range. Based on the flood event peak flows examined in this study, the potential for substantial sediment movement within short durations highlights the importance of future studies focusing on rapid reduction in small streams burdened with heavy sediment loads. Also, the abundant volume of water released during the Shishper GLOF event in May 2022 draws attention to the sophisticated



Fig. 4. Hydrograph illustrating the Shishper GLOF with the triangle denotes peak water discharge on June 22nd, 2019, recorded at 141.58 m³/s.



Fig. 5. Hydrograph depicting the Shishper GLOF with the triangle indicating peak water discharge recorded on May 29th, 2020, at 84.94 m³/s.



Fig. 6. Hydrograph illustrating the catastrophic Shishper GLOF with the triangle indicating peak water discharge recorded on May 07th, 2022, at $226.53 \text{ m}^3/\text{s}$.

interconnectedness of glacial dynamics and climatic factors. This emphasizes the need for a comprehensive assessment and continuous monitoring of individual glacial lakes to mitigate the GLOF-associated risks on downstream communities in the Karakoram ranges of Northern Pakistan.

CRediT authorship contribution statement

Mehtabidah Ali: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e35951.

References

- W. Hussain, M.A. Khan, Climate change-induced Glacial Lake Outburst Floods in Hunza Valley of Pakistan: an assessment of indigenous farming community perceptions and adaptation, Environ. Dev. Sustain. (2023), https://doi.org/10.1007/s10668-023-03396-6.
- [2] A. Ashraf, R. Naz, M.B. Iqbal, Altitudinal dynamics of glacial lakes under changing climate in the Hindu Kush, Karakoram, and Himalaya ranges, Geomorphology 283 (2017) 72–79, https://doi.org/10.1016/j.geomorph.2017.01.033.
- [3] J.J. Clague, S.G. Evans, A review of catastrophic drainage of moraine-dammed lakes in British Columbia, Quat. Sci. Rev. 19 (17–18) (2000) 1763–1783.
- [4] S. Harrison, D. Jones, K. Anderson, S. Shannon, R.A. Betts, Is ice in the Himalayas more resilient to climate change than we thought? Geogr. Ann. Phys. Geogr. 103 (1) (2021) 1–7, https://doi.org/10.1080/04353676.2021.1888202.

M. Ali

- [5] M.J. Westoby, N.F. Glasser, J. Brasington, M.J. Hambrey, D.J. Quincey, J.M. Reynolds, Modelling outburst floods from moraine-dammed glacial lakes, Earth Sci. Rev. 134 (2014) 137–159.
- [6] W. Wang, X. Yang, T. Yao, Evaluation of ASTER GDEM and SRTM and their suitability in hydraulic modelling of a glacial lake outburst flood in southeast Tibet, Hydrol. Process. 26 (2) (2012) 213–225, https://doi.org/10.1002/hyp.8127.
- [7] D. Li, X. Lu, D.E. Walling, T. Zhang, J.F. Steiner, R.J. Wasson, S. Harrison, S. Nepal, Y. Nie, W.W. Immerzeel, High Mountain Asia hydropower systems threatened by climate-driven landscape instability, Nat. Geosci. 15 (7) (2022) 520–530.
- [8] K. Hewitt, The Karakoram anomaly? Glacier expansion and the elevation effect, Karakoram Himalaya, Mt. Res. Dev. (2005) 332-340.
- [9] T.G. Longstaff, Glacier exploration in the Eastern Karakoram, Geogr. J. (1910) 622-653.
- [10] X. Yao, S. Zhou, M. Sun, H. Duan, Y. Zhang, Surging glaciers in high mountain Asia between 1986 and 2021, Rem. Sens. 15 (18) (2023), https://doi.org/ 10.3390/rs15184595. Article 18.
- [11] V. Kapitsa, M. Shahgedanova, H. Machguth, I. Severskiy, A. Medeu, Assessment of evolution and risks of glacier lake outbursts in the Djungarskiy Alatau, Central Asia, using Landsat imagery and glacier bed topography modelling, Nat. Hazards Earth Syst. Sci. 17 (10) (2017) 1837–1856.
- [12] V. Round, S. Leinss, M. Huss, C. Haemmig, I. Hajnsek, Surge dynamics and lake outbursts of Kyagar glacier, Karakoram, Cryosphere 11 (2) (2017) 723–739.
 [13] I. Rashid, U. Majeed, A. Jan, N.F. Glasser, The January 2018 to September 2019 surge of Shisper Glacier, Pakistan, detected from remote sensing observations, Geomorphology 351 (2020) 106957.
- [14] G. Khan, S. Ali, X. Xiangke, J.A. Qureshi, M. Ali, I. Karim, Expansion of Shishper Glacier lake and recent glacier lake outburst flood (GLOF), Gilgit-Baltistan, Pakistan, Environ. Sci. Pollut. Control Ser. 28 (2021) 20290–20298.
- [15] S.R. Bajracharya, P. Mool, Glaciers, glacial lakes and glacial lake outburst floods in the Mount Everest region, Nepal, Ann. Glaciol. 50 (53) (2009) 81–86, https://doi.org/10.3189/172756410790595895.
- [16] N. Khadka, X. Chen, S. Sharma, B. Shrestha, Climate change and its impacts on glaciers and glacial lakes in Nepal Himalayas, Reg. Environ. Change 23 (4) (2023) 143, https://doi.org/10.1007/s10113-023-02142-y.
- [17] V. Agarwal, M. Van Wyk de Vries, U.K. Haritashya, S. Garg, J.S. Kargel, Y.-J. Chen, D.H. Shugar, Long-term analysis of glaciers and glacier lakes in the Central and Eastern Himalaya, Sci. Total Environ. 898 (2023) 165598, https://doi.org/10.1016/j.scitotenv.2023.165598.
- [18] R. Bhambri, C.S. Watson, K. Hewitt, U.K. Haritashya, J.S. Kargel, A. Pratap Shahi, P. Chand, A. Kumar, A. Verma, H. Govil, The hazardous 2017–2019 surge and river damming by Shispare Glacier, Karakoram, Sci. Rep. 10 (1) (2020) 4685, https://doi.org/10.1038/s41598-020-61277-8.
- [19] A.V. Rowan, D.L. Egholm, D.J. Quincey, N.F. Glasser, Modelling the feedbacks between mass balance, ice flow and debris transport to predict the response to climate change of debris-covered glaciers in the Himalaya, Earth Planet Sci. Lett. 430 (2015) 427–438.
- [20] S.D. Richardson, J.M. Reynolds, An overview of glacial hazards in the Himalayas, Quat. Int. 65 (2000) 31-47.
- [21] M.M. Bennett, N.F. Glasser, Glacial Geology: Ice Sheets and Landforms, John Wiley & Sons, 2011.
- [22] D.J. Quincey, S.D. Richardson, A. Luckman, R.M. Lucas, J.M. Reynolds, M.J. Hambrey, N.F. Glasser, Early recognition of glacial lake hazards in the Himalaya using remote sensing datasets, Global Planet. Change 56 (1–2) (2007) 137–152.
- [23] R.P. Kumar, M.V. Narayan, Changes of glacier lakes using multi-temporal remote sensing data: a case study from India, Geographica Pannonica 21 (3) (2017) 132–141.
- [24] P.I. Anacona, J. Kinney, M. Schaefer, S. Harrison, R. Wilson, A. Segovia, B. Mazzorana, F. Guerra, D. Farías, J.M. Reynolds, N.F. Glasser, Glacier protection laws: potential conflicts in managing glacial hazards and adapting to climate change, Ambio 47 (8) (2018) 835–845, https://doi.org/10.1007/s13280-018-1043-x.
- [25] W.T. Pfeffer, A.A. Arendt, A. Bliss, T. Bolch, J.G. Cogley, A.S. Gardner, J.-O. Hagen, R. Hock, G. Kaser, C. Kienholz, The Randolph Glacier Inventory: a globally complete inventory of glaciers, J. Glaciol. 60 (221) (2014) 537–552.
- [26] S. Muhammad, J. Li, J.F. Steiner, F. Shrestha, G.M. Shah, E. Berthier, L. Guo, L. Wu, L. Tian, A holistic view of Shisper Glacier surge and outburst floods: from physical processes to downstream impacts, Geomatics, Nat. Hazards Risk 12 (1) (2021) 2755–2775, https://doi.org/10.1080/19475705.2021.1975833.
- [27] L. Copland, T. Sylvestre, M.P. Bishop, J.F. Shroder, Y.B. Seong, L.A. Owen, A. Bush, U. Kamp, Expanded and recently increased glacier surging in the Karakoram, Arctic Antarct. Alpine Res. 43 (4) (2011) 503–516, https://doi.org/10.1657/1938-4246-43.4.503.
- [28] D. Karim, I. Karim, W. Anwar, K. Uddin, A. Ali, D.R. Gurung, Glacier hazard associated with surging glaciers-story of the Shishper Glacier from Hunza, Pakistan, Ceлевые Потоки: Karacropoha, Puck, Прогноз, Защита (2020) 234–245. https://www.researchgate.net/profile/Deedar-Barcha/publication/346943035_Glacier_ hazard_associated_with_surging_glaciers_story_of_the_Shishper_Glacier_from_Hunza_Pakistan/links/5fd33e6b45851568d1555fc9/Glacier-hazard-associatedwith-surging-glaciers-story-of-the-Shishper-Glacier-from-Hunza-Pakistan.pdf.
- [29] H. Xu, Modification of normalised difference water index (NDWI) to enhance open water features in remotely sensed imagery, Int. J. Rem. Sens. 27 (14) (2006) 3025–3033, https://doi.org/10.1080/01431160600589179.
- [30] M. Zhang, H. Zhao, F. Chen, J. Zeng, Evaluation of effective spectral features for glacial lake mapping by using Landsat-8 OLI imagery, J. Mt. Sci. 17 (11) (2020) 2707–2723.
- [31] C. Huggel, A. Kääb, W. Haeberli, P. Teysseire, F. Paul, Remote sensing based assessment of hazards from glacier lake outbursts: a case study in the Swiss Alps, Can. Geotech. J. 39 (2) (2002) 316–330, https://doi.org/10.1139/t01-099.
- [32] M.J. Roberts, JÖkulhlaups: a reassessment of floodwater flow through glaciers, Rev. Geophys. 43 (1) (2005) 2003RG000147, https://doi.org/10.1029/ 2003RG000147.
- [33] M. Rafiq, S.A. Romshoo, A.K. Mishra, F. Jalal, Modelling Chorabari Lake outburst flood, Kedarnath, India, J. Mountain Sci. 16 (1) (2019) 64–76. https://doi. org/10.1007/s11629-018-4972-8.
- [34] Pakistan Meteorological Department. (n.d.). Retrieved March 2, 2024, from https://www.pmd.gov.pk/en/.
- [35] H. Singh, D. Varade, M.V.W. de Vries, K. Adhikari, M. Rawat, S. Awasthi, D. Rawat, Assessment of potential present and future glacial lake outburst flood hazard in the Hunza valley: a case study of Shisper and Mochowar glacier, Sci. Total Environ. 868 (2023) 161717, https://doi.org/10.1016/j.scitotenv.2023.161717.