Case Study

Formation of a hazardous ice-dammed glacier lake: a case study of anomalous behavior of Hassanabad glacier system in the Karakoram

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Abstract
Formation of glacier lakes and glacier lake outburst floods (GLOF) are not a new phenomenon in the Karakoram Himalaya. This case study focuses on sudden expansion of Shishper glacier termini and subsequent formation of an ice-dammed glacier lake occupying ~ 3 km moraine following Mochuwar glacier retreat in the Karakoram. A method based on a combination of space (remote sensing) and ground observations is applied to reconstruct spatio-temporal glacier termini change and lake extent. Moreover, the likely glacier-mass losses are determined above and below the Equilibrium Line Altitude (ELA) contours based on recommended values of Accumulation-Area-Ratio and Accumulation-Area-Balance-Ratio for mountain glaciers. Potential implications of glacier surge and ice-dammed glacier lake on downstream infrastructure and hydrological system are assessed. The results show that the Shishper glacier termini advanced 90% from 1980s to 1999 and 78.7% from 1999 to 2019 as compared to 188% and 421% retreat in the Mochuwar glacier termini for the same years, respectively. The current unusual surge of debris-covered Shishper glacier termini created a ~ 152 m deep ice-dammed glacier lake representing a total area increase of 500% over 6 months. The ratio of glacier accumulation to ablation is low for the Hassanabad glacier system, therefore there is a significant influence on forward movement of Shishper glacier termini. Water discharge from the glacier lake increased with increase in summer temperatures causing inundation of part of the Karakoram Highway at Hassanabad village. The current unusual surge of the Shishper glacier can be characterized as type-I as it involves an in-built unsteadiness without any regular intervals due to an unknown mechanism producing very high movement of debris-covered glacial ice and sediments.

Keywords Karakoram · Ice-dammed lake · Hypsometry

1 Introduction

The almost 500 km long Karakoram Mountain range covers ~ 207,000 km^2 area in parts of China, Pakistan, India, Tajikistan and Afghanistan. This range occupies the largest glaciated areas in the world excepting the Polar Regions. About 5218 glaciers covering 15,040 km^2 area [5] and 2420 lakes [23] in Northern Pakistan encompass portions of the three mountain ranges of the Hindu-Kush, Himalaya, and Karakoram. The junction of these three mountain ranges, high seismic processes, steep slopes and a combination of a variety of high-pitched mountains, glaciers and their unique geomorphological characteristics [11] are considered to be major factors responsible for an extensive diversity of natural hazards (e.g. flash floods, landslides, avalanches, and glacial lake outburst floods (GLOF)) [19].

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Historically, evidence of 35 destructive outburst floods have been recorded in the Karakoram region in the past 200 years [2] with 17 in the Upper Indus [16] and 20 in the Himalaya. Especially, in the Karakoram, new GLOFs have developed since 2010 due to the rapid melting or surging of glaciers and climate change, causing potential threats to downstream settlements and infrastructures. Over 36 glacier lakes have been assessed to be on the verge of outburst with probable hazardous GLOFs [36]. Especially, Shimshal valley in the Western Karakoram, Shyok river basin in the Eastern Karakoram and Chitral valley in the Hindu-Kush [1] are known localities for disaster-prone GLOFs in the last two decades. The Khurdopin glacier, in Shimshal valley, advanced an average of ~ 18 m /day in the 3 months from April 2017 to May 2017 [26]. Historically, two GLOF related disaster events triggered in the Shimshal and Karambar valleys in the year 1905 are reported to be the most catastrophic outbreak events [18]. In recent times, out of the total 2,500 glacier lakes of Northern Pakistan, 33 are reported to be potentially dangerous [9, 31]. About 146 GLOF events have been documented resulting in 30 major disasters [8]. Five GLOF-related events were reported in the Gojal valley of Karakoram Himalaya in 2008 [23], 13 from 2001 to 2016 and 44 from 1826 to 2000 in the Upper Indus [6]. These lakes are considered to be risky GLOF environments, which can release millions of cubic meters (m^3) of melt water and debris, resulting in the loss of property, lives, and means of support amongst the isolated and underprivileged mountain societies [20].

As the current prominence of known GLOFs is changing, the number of potentially risky lakes and their status is fluctuating. Moreover, new GLOFs are emerging swiftly due to glacier fluctuations. These fluctuations are irregular [7] and sudden [17] caused by surge-type glaciers [15]. Glacier surges in the Karakoram are categorized by two comparatively small dynamic stages: (1) surges continue for more than a few months, or (2) for a few years [10]. Especially, stage-1 type of surges have a potentially negative impact on the livelihood of downstream mountain communities, which are at risk of upsurge flooding linked with glacier hydrological variations, and from ice-dammed lake bursting due to the forward movement of glacier termini into trunk valley rivers [28]. On the other hand, creations of likely risky lakes and/or new GLOFs are on the rise due to a few retreating glaciers [3] as well. For the last 2 years, rapidly emerging tendency of glacier lakes creation in Shimshal and Passu valleys of Hunza river basin is associated with the surge-type glaciers [7].

This case study focuses on sudden expansion of Shishper glacier termini and subsequent formation of an ice-dammed glacier lake occupying ~ 3 km moraine following Mochuwar glacier retreat in the Karakoram. Previously, the Shishper glacier surged at least three times (1904–1905, 1972–1976, and 1993–2002) (NASA Earth Observatory, Rocky [32]. The highest surge was reported in the month of August 2018 [13]. No evidence of formation of ice-dammed lake is reported from earlier surges. The current unusual surge is responsible for the formation of the lake. This unusual surging has created a high degree of uncertainty among the 5000 inhabitants living in the seven downstream mountain settlements (Hassanabad, Murtazabad, Fiker, Askurdas, etc.) of Hunza and Nagar valleys (Fig. 13), primarily due to speculations based on limited or no scientific/remote sensing data and future projections pertaining to the extent and implications of potential disasters. Therefore, it is imperative to determine the current state and extent of the Shishper and Mochuwar glacier termini and the volume of the newly formed lake. Secondly, presently there is no convincing conclusion as to why Shishper glacier of the Hassanabd glacier system is behaving in a different way from the retreating neighboring Mochuwar glacier even though they are like two-fold brothers. This is a complete anomaly.

In order to find answers to this question, our study aims to achieve three objectives: (1) spatio-temporal state of the confluence of Hassanabad glacier system of Shishper basin based on an initial assessment [4], (2) estimation of the likely glacier-mass losses above and below the Equilibrium Line Altitude (ELA) contours, and (3) potential implications of glacier surge and ice-dammed glacier lake on downstream infrastructure and hydrological system. Firstly, the past and current behaviors of the termini of both glaciers are mapped and assessed based on recent observations through ground surveys, informal field-interviews of locals/community representatives, satellite imagery and secondary data obtained from GBDMA [12]. By using GIS and remote sensing technology, temporal changes are recorded in terms of the geographic extent, depth and water-volume of the newly formed lake. Secondly, because all glaciers require to outhouse glacier-mass that has been accumulated in their higher elevations previously [27], glacier mass-balance based on ELA estimation is obtained taking Accumulation-Area-Ratio (AAR) and Accumulation-Area-Balance-Ratio (AABR) into account. Thirdly, this paper analyses broad susceptibility profile and potential implications for downstream communities, public infrastructure, and land in case of outhousing of glacier-mass by the surging Shishper glacier or newly formed ice-dammed glacier lake outburst. Risks posed to installations like hydropower stations, water transport channels for agriculture, water tanks of hydropower water channels, houses, small industries, an Army Camp, and the Hassanabad Bridge constructed on the Karakoram Highway (KKH) (see Fig. 13) in the worst case scenario are identified and mapped. These scenarios are compared with earlier estimates made by GBDMA. A number of recommendations with respect to the establishment of Glacier Monitoring System, mitigation plans and Early Warning System are made.

2 Topographic setting and spatial extent

Shishper River basin occupying Hassanabad glaciers is situated in the Hunza valley of Western Karakoram mountain range (36°17′–36°32′ N/74°22′30″–74°41′ E, Fig. 1a). The western watershed of the glacier system is called Mochuwar while the eastern watershed is known as the Shishper. These two tongues glaciers combine together at the confluence and fed the Hunza River. The maximum catchment extent in the east is the peak Shishper (7611 m). This basin is categorized by an extreme geomorphological gradient, ranging from 1,937 m up to 7,735 m at the summit of Mochuwar in the west and 2486 m to 7400 m in the east at Shishper. Glaciers of the basin belong to the Passu mountain group of glaciers. Out of the total 365 km^2,

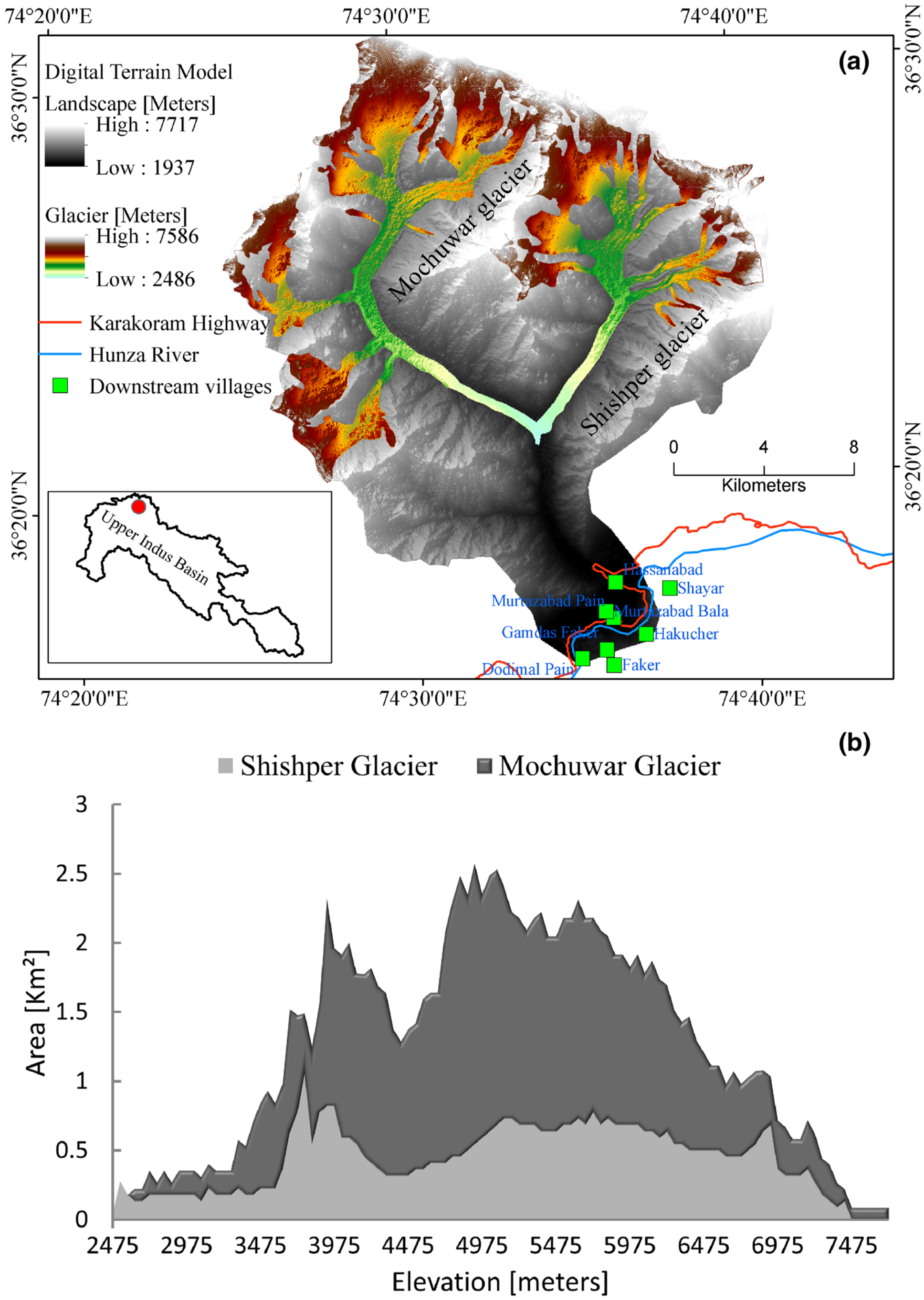


Fig. 1 Map of the study area (Shishper river basin) lies in the Western Karakoram, occupying two glaciers (Shishper and Mochuwar), nearby KKH, Hunza River and human settlements (**a**) a comparison of percentage distribution of hypsometries (glacial-ice-area proportional to elevation) of Hassanabad glaciers (Shishper glacier and Mochuwar glacier) (**b**)

the glaciated area of the basin is about 133 km^2. Majority of the Shishper basin is covered by supra-glacial fragments, similar to the other glaciers of the Karakoram. The topographical venue of the basin makes a kite-like shape, valley-like basin sections and narrow ravine like gorge sections. This basin originates in the Shander Shaindar Pass in the west. For the last many years, most of the basin has been fed by water-outflow from Mochowar glacier (east basin).

A geographic map representing the distribution of altitudes and the nearby KKH and Hunza river in the study area is shown in Fig. 1a. A large proportion (43.4%) of the total area of the study area lies between elevations 3500–4700 m followed by 37.8% between 4700 and 6000 m. At higher elevation, 2.7% of the area lies between 6000–7717 m while 16.1% lies between 1937 and 3500 m.

Glaciation is one of the significant factors in modelling the topography of the Shishper basin with maximum glaciation on higher elevations. This basin encompasses two valley glaciers namely Shishper and Mochuwar while several smaller cirque glaciers exist in the higher stretches. Mochuwar glacier, parallel to Shishper glacier, is situated to the north-west stretching towards the south-east. A histogram comparing hypsometric distribution of elevations and area (in %) occupied by Shishper and Mochuwar glaciers is presented in Fig. 1b. The glacial-ice-area occupied by Shishper glacier, 18 km long and covering 45 km^2 area, lies between 2478 and 7450 m and Mochuwar glacier, 22 km long and covering 88 km^2 area, lies between 2626 and 7737 m. The slope of Shishper glacier (35.1) is higher than Mochuwar (32.2). Mochuwar glacier has an aspect of 164 as compared to 161 of Shishper glacier. A large proportion (38.5%) of the total glacial ice area of both glaciers lies between elevations 4920–6100 m followed by 31% between 3800 and 4920 m. At higher elevation, 19.3% glacial ice area lies between 6100 and 7586 m while the lowest proportion of area (11.2%) lies between 2486 and 3800 m. A large proportion (35.5%) of the total glacial ice area of the Mochuwar glacier lies between elevations 4400–5400 m as compared to 24% of Shishper glacier at the same elevation. There is a slight difference between percentages of glacial ice area of both glaciers between 5400 and 6400 m. Shishper glacier termini occupy higher glacial ice as compared to Mochuwar indicating instability of debris present at lower elevation. Sudden surge may move this unstable material downwards resulting in disconnection of confluence and blockage of pedestrian paths to both valleys at lower elevation.

3 Methodology flowchart, material and methods

Methodology flowchart (Fig. 2) comprises of datasets, delineation of glacier changes and ice-dammed lake growth and mapping of potential damages to downstream hydrological systems and other infrastructure due to glacier surge and water discharge from the glacier lake.

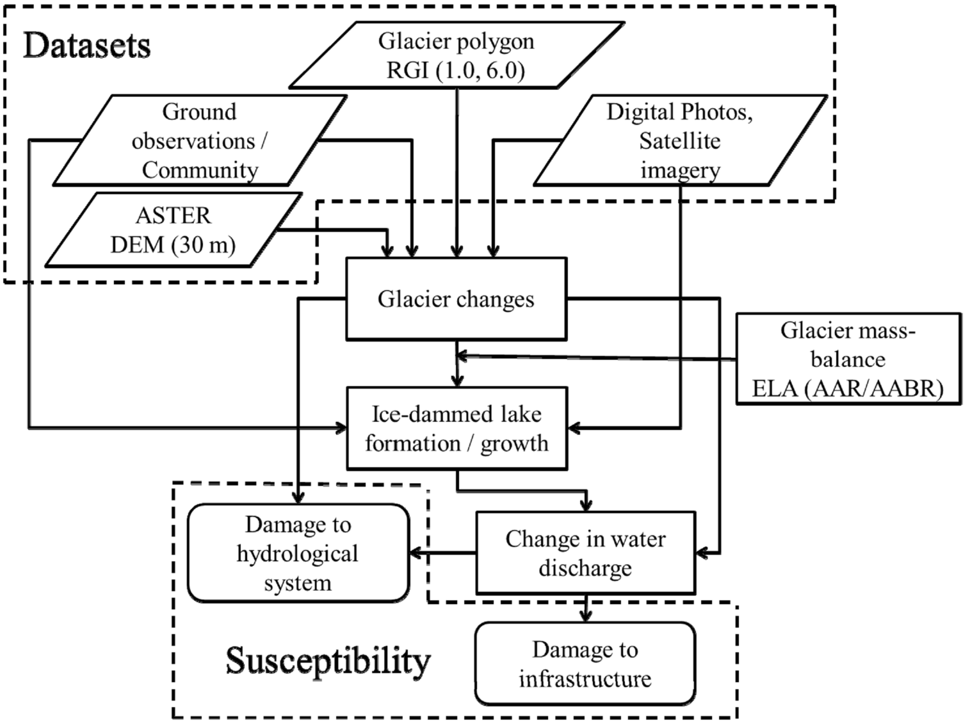


Fig. 2 Methodology flowchart comprise of datasets (glacier polygons, topographic information, ground observations / informal community interviews, digital photographs and satellite imagery), delineation of glacier changes and ice-dammed lake growth and mapping of damages to hydrological systems and other infrastructure due to glacier surge and water discharge from glacier lake

Datasets include glacier polygons, topographic information, ground observations / informal community interviews, digital photographs and satellite imagery. The baseline glacier outlines are based on Randolph Glacier Inventory (RGI) datasets. Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER). Global Digital Elevation Model (GDEM2) (https://earthexplorer.usgs.gov/) are used to obtain topographic information of glaciers and glacier lake and to estimate ELA, the separating contour between accumulation and ablation zones of glaciers, and glacier-climate reconstructions. Digital photographs and satellite imagery are used to delineate glacier and ice-dammed glacier lake changes and glacier terminus positions. Information obtained from satellite imagery is cross-verified from ground observations. Potential and already damaged downstream infrastructure and hydrological systems are mapped from glacier changes and information about discharge of seepage water from glacier dammed Ice Lake.

Specifically, the outlines of these two glaciers (Shishper and Mochuwar) are based on the Randolph Glacier Inventory (RGI) V. 1.0 [34] and V. 6.0 [33] for earlier years (e.g. 1980, 1999) which provided a combined glacier outlines for both glaciers of the Hassanabad glacier system. Glacier terminus polygons of these glaciers were improved manually and validated with digital photographs taken in different months, sketches (Fig. 3a) and photographs (Fig. 3b) [12], satellite imagery (Rocky [32] (https://www.rockyglaciers.org/debris_covered_glaciers/shishper.html) and the 30 m resolution ASTER GDEM2. For glacier and ice-dammed glacier lake polygons, terminus position changes were mapped using month-wise Planet Explorer imagery (https://www.planet.com/explorer/), which allowed us to determine whether the terminus of Shishper and Mochuwar glaciers were advancing, stable, or retreating during the observation period in 2018–2019. Additionally, two reports by GBDMA titled: Situation Report, prepared after an aerial visit in an Army Helicopter on November 29, 2018 were used for cross verification.. Informal interviews, which did not include any questionnaires, of a few community members were conducted. Two local miners were asked about their first observation of the glacier's movement. Three shepherds, who were trapped for a week were also inquired regarding the date of the sudden advancing of Shishper glacier. We also got historical information from some locals about the Shishper glacier surges. A few of the interviews of these local residents pertaining to the movement and damages caused by Shishper glacier surge are available on https://www.youtube.com/watch?v=gvIMxsK2-dI. Additionally, two local hunters provided valuable information about surging.

The termini of Shishper glacier (Fig. 3c) moved forward unlike Mochuwar glacier. In such cases, the ELA shifts.

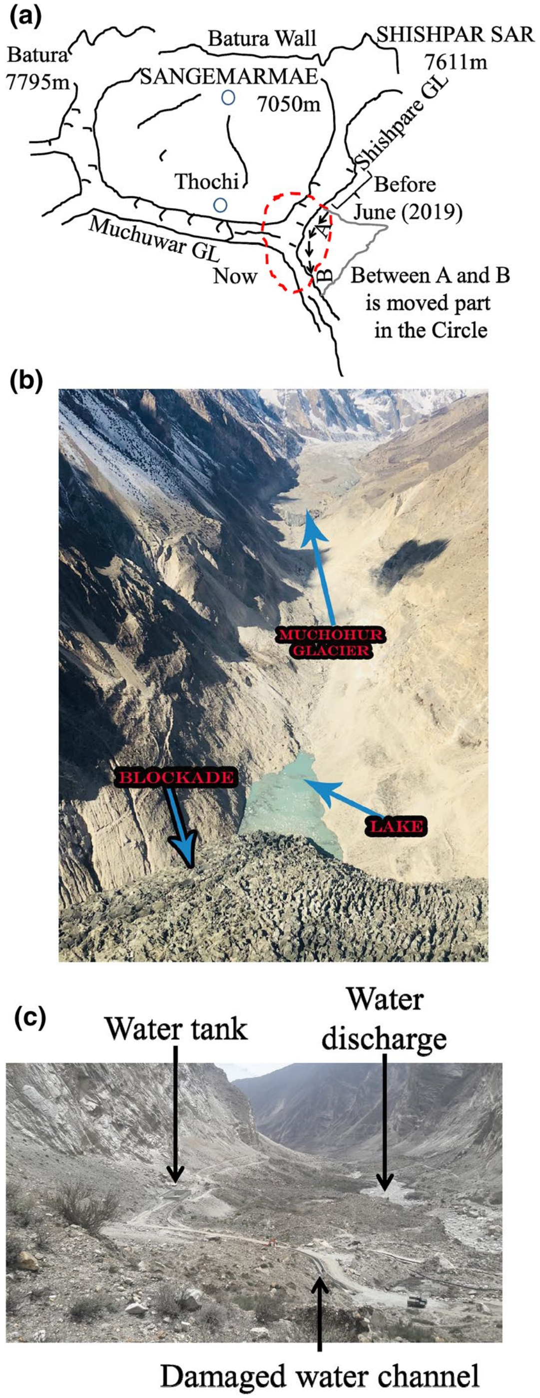


Fig. 3 Strata of the glacier system through a sketch and photographs taken on November 29, 2018. Sketch of the glacier system provide location and direction of movement (**a**) An aerial photograph representing Glacier Lake dammed by the surging Shishper glacier and moraine following Mochuwar glacier retreat (After [12] (**b**), the downstream water channels and water tanks damaged or under threat from surging of the glacier (**c**)

Therefore, it is imperative to know the position of the ELA of Hassanabad glacier system. But there is a lack of field-based climatic and mass-balance calibrations for Hassanabd glacier system. Therefore an indirect method for glacier-climate reconstructions was applied by using an automatic tool developed by Pellitero et al. [25] based on implicit and optimal reference values of AAR and AABR for mountain glaciers. Additionally, the likely future mass loss / gain of this glacier system was determined above and below the ELAs as climatic conditions, glacier hypsometry and ELA are considered to be good indicators of the response time of glacier volume. AAR and AABR index values for different types of glaciers are recommended in the scientific literature [29, 30]. Some of the recommended values of AABR are as follows: global (1.75 ± 0.71), High-latitude (2.24 ± 0.85) and Central Asia (1.75 ± 0.56). Therefore, we used the reference value of 0.6 for AAR and 2.24 ± 0.85 for AABR. Additionally, hypsometric curves for the glaciated landscape of Hassanabad glacier system derived from ASTER DEM were interpreted based on a highly generalized model developed from climatic data (2007–2010) by Mukhopadhyay and Khan [24].

4 Results and analysis

4.1 ELA for glacier equilibrium and climatic regimes

We estimated zero net-balance ELAs of glacier system and assumed this system is in equilibrium with climatic conditions. Figure 4 shows a map of reconstructed glacial-ice areas and contours corresponding to estimated zero net-balance ELAs of Hassanabad glacier system. Based on recommended values of AAR and AABR for mountainous regions, a linear regression examination recommends that the zero net-balance ELA is 5,474 m for AAR = 0.6 and 5,141 m for AABR = 2.24 (Fig. 4a). Furthermore, ratios between accumulation-area, ablation-area and the total glacial-area of these glaciers are estimated respectively for the AAR and AABR values (Fig. 4b). The majority (41.68% of area) of the Hassanabad glaciers lies at transitional altitudes, especially in the 4000–6000 m region where the hypsometric curve is much flatter. The ELA accumulation-area is limited to the vertical (steeper) region of the curve below 5,400 m covering 27% accumulation-area for AAR (0.6) as compared to below 5441 m covering 45% accumulation-area for AABR (2.24) to the total glacial area. These glaciers receive more snow (inputs) and accumulation in their higher elevations, and lose more mass by ablation in their lower elevations. However, the ratio of accumulation-area to ablation-area is larger (27:73) for AAR and smaller (45:55) for AABR and is therefore a significant influence on forward behavior. This is one of the reasons why such glaciers are considered to be in steady-state and even advancing [14].

About 19% of the glacier area lies in the net freezing or no ablation zone while ~ 11.54% lies in the avalanche nourishment zone. About 13% glacier area lies at the freezing level or 0 °C isotherm representing the elevation where the temperature is at freezing-point of water. About 5.92% of the glacier area is occupied by glacier terminus (including debris, basal slide area) while about 7.46% of the area is occupied by perennial snow and ice lying on net accumulation / low velocity zone. Despite slight variation in climatic conditions of both glaciers, anomaly pertaining to glacier termini retreat and advancing still persists as Mochuwar glacier retreats while Shishper glacier advances. This shows that temperature is not a sole factor in the sudden surge of the Shishper glacier. However, high precipitation in the winter of 2018 and subsequent weight and forcing may be one of the factors in the unusual advancing of Shishper glacier.

4.2 Spatio-temporal state of confluence of the Hassanabad glacier system

Until the 1980s, both glaciers of Shishper basin congregated into each other to form a confluence but, since 1999, Mochuwar glacier has retreated ~ 3 km and detached itself from Shishper glacier. As a result of the retreat, the glacier moraine with a long, almost 500 m deep gap formed an ice-dammed glacier lake at the confluence. Furthermore, until 1999, glacier termini of both glaciers were retreating. Mochuwar glacier terminus is continuously retreating while Shishper glacier terminus abnormally surged. The first abnormal moment of Shishper glacier termini was observed during the month of April, 2018 by local inhabitants and cross-checked from satellite imagery. This surge is continuing up to now and the glacier terminis has touched the facing mountain resulting in a blockage of melt water from Mochuwar glacier which contributes 80% of Hassabad River and its own melt-flow. The blockage site is ~ 8 km from the KKH passing through Hassanabad village. Ground observations revealed that by March, 2019, 90% of the normal discharge was halted affecting supply of water for electricity-generation to three main villages (Hassanabad, Murtazaabad and Aliabad). However, seepage melt water increased with increase in summer temperatures. Sudden discharge of melt water inundated part of the KKH at Hassanabad village on June 23, 2019. Previously both adjacent glaciers were responsible for the surges with large movements and reckless flow. The current surge of the Shishper glacier can be characterized as type-I based on categories made by Meier and Post [21] as it involves an in-built unsteadiness without any regular

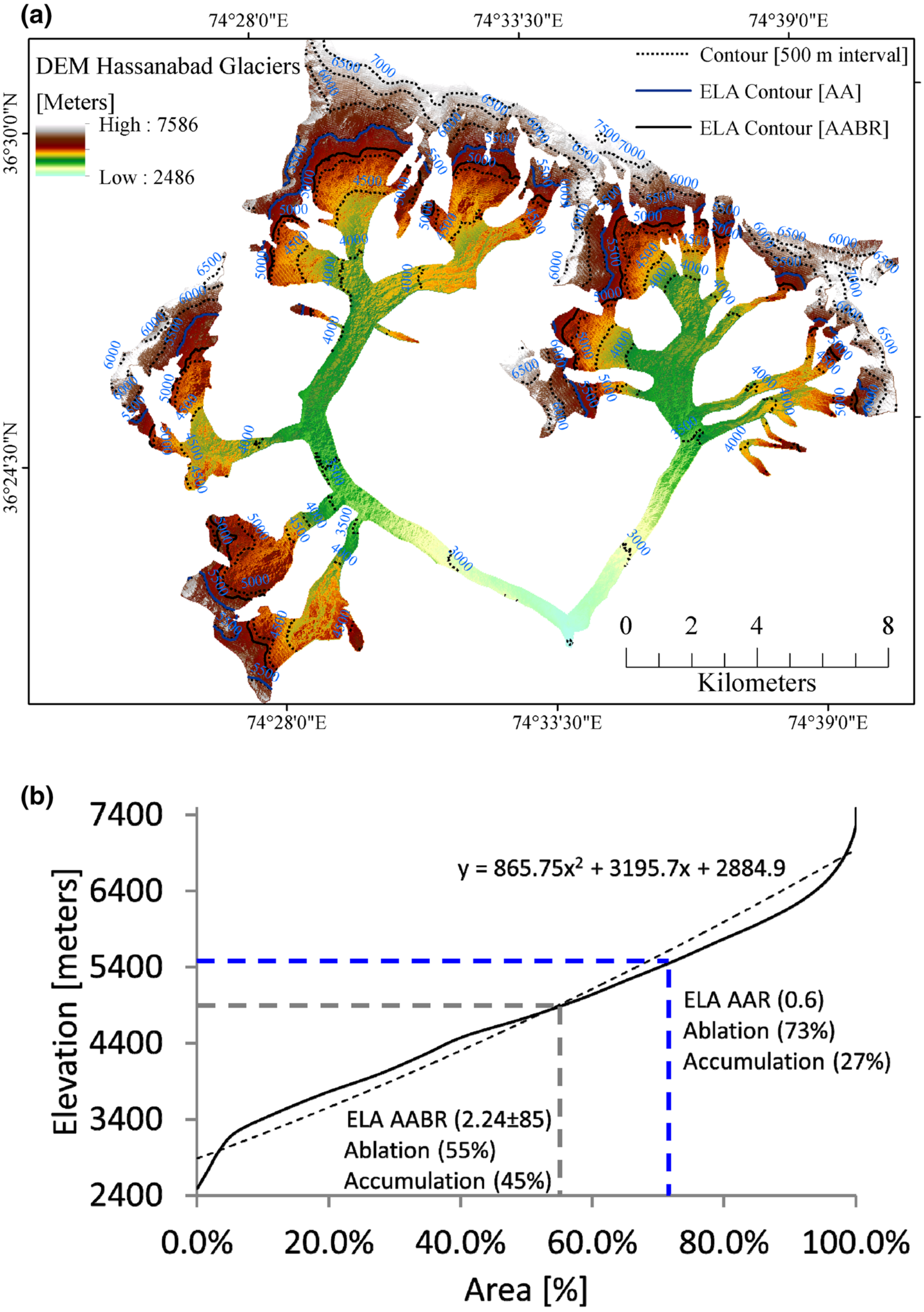


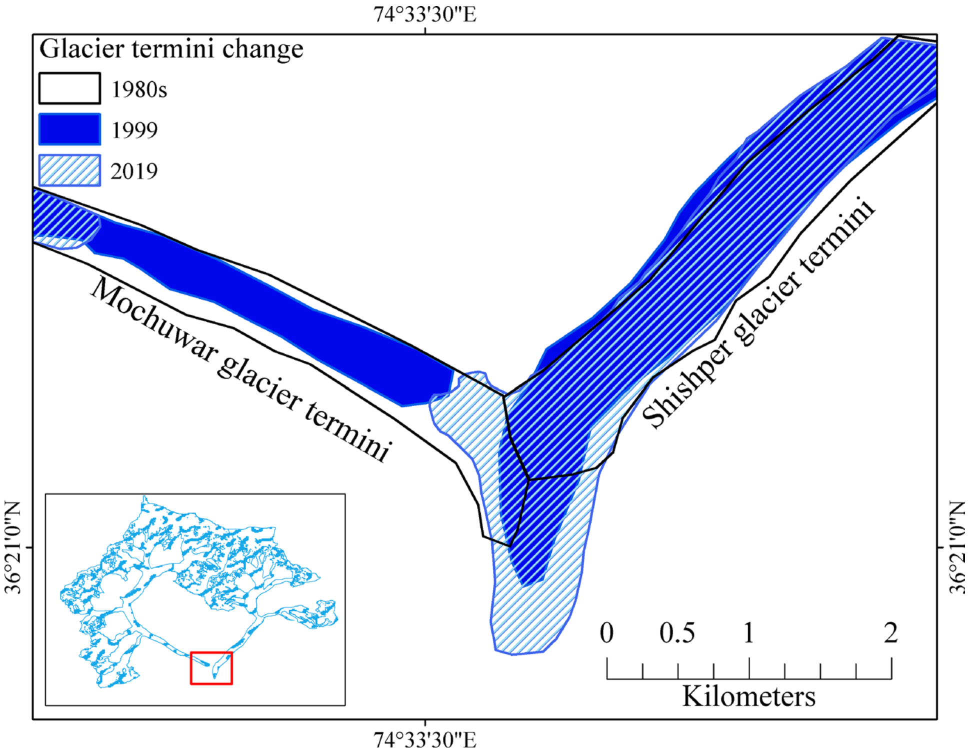
Fig. 4 Map of reconstructed glacial-ice zones along with its distribution within contour interval of 500 m and geographic position of Equilibrium Line Altitude (ELA) Area Accumulation Ration (AAR) and Accumulation Area Balance Ratio (AABR) corresponding to estimated zero net-balance Hassanabad glaciers (**a**). A graph representing ratio of ablation and accumulation areas obtained from zero-net balance ELA (AAR) and (AABR) of Hassanabad glacier system. Normalized elevation is plotted against their corresponding cumulative percentage (%) area of the glacial-ice surface and correlation coefficient of polynomial trend line (order 2) (**b**)

intervals due to an unknown mechanism producing very high movement of sediment.

A geographic map representing the status of the termini of both glaciers (45.71 km^2 Shishper and 88 km^2 Mochuwar) for 3 years (1980, 1999 and 2019) is depicted in Fig. 5. These maps are based on two glacier datasets for the 1980s and 1999 and on ground observations for different months of 2018 and 2019. The Shishper glacier termini advance represents an increase of 90% in ~ 20 years from 1980s to 1999. The highest 78.7% surge is reported in the 20 years from 1999 to 2019. In contrast with Shishper glacier termini, the Mochuwar glacier termini are indicating a total decrease of 188% in the ~ 20 years from 1980s to 1999. The highest 421% decline is reported in the 20 years from 1999 to 2019.

A comparison of Shishper glacier termini surge through pictures taken in different time periods is presented in Fig. 6. Accordingly to initial assessment, in July, 2018 the glacier stretched significantly north-west to south-west. Although minor movements were observed for the last 2 years, since May–June 2018 a drastic forward and upward expansion has been observed. The

Fig. 5 Spatio-temporal state of confluence of Shishper and Mochuwar glaciers. Geographic extent of glacier terminus for the years (1980s, 1999 and 2019) indicating confluence detachment along with a decreasing trend in the glacial ice area covered by Mochuwar and an increasing trend in Shishper glacier and a graph representing spatio-temporal glaciers termini change over the same years



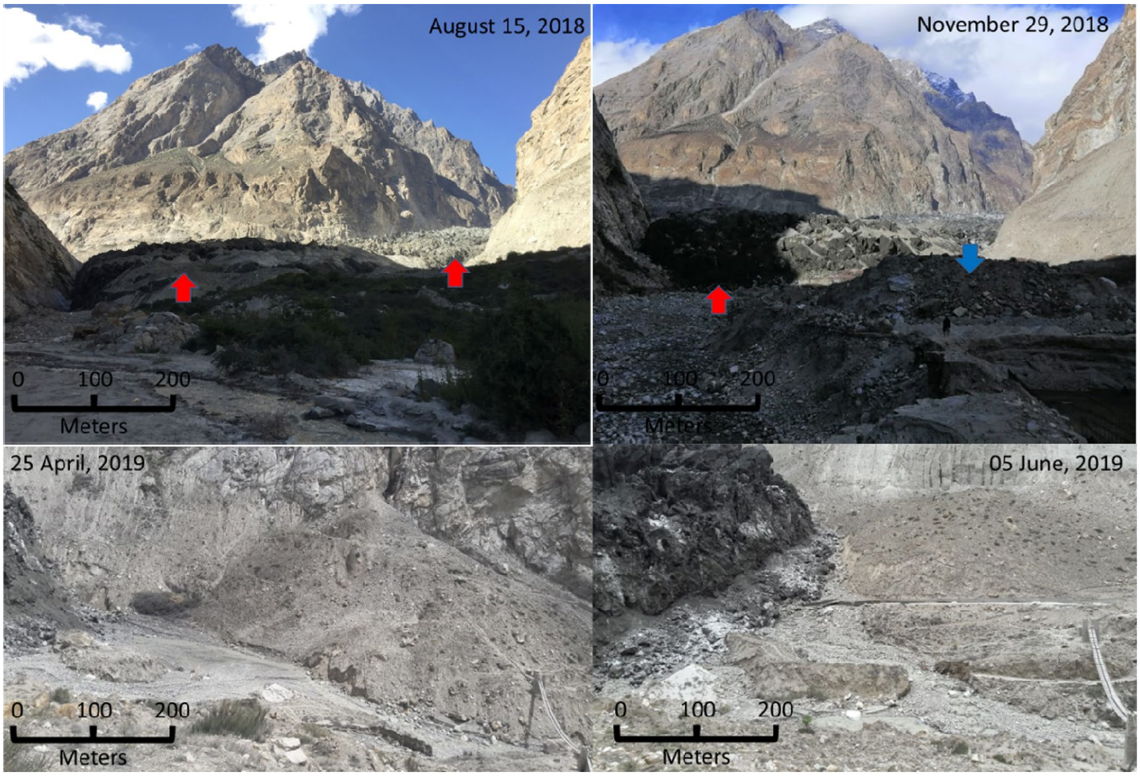


Fig. 6 A comparison of Shishper glacier termini surge through pictures taken in different time periods. Size/quantity or glacier material present at upper and lower portions of glacier termini is indicated with up-arrows in the picture taken on August 15, 2018. An increase in the material at the upper portion of glacier termini is indicated by up-arrow and decrease by down-arrow (picture taken on November 29, 2018). A comparison of geographic location of glacier termini and a bridge used to pass water pipe to transport potable stream water to downstream settlements (pictures taken on April 25, 2019 and June 05, 2019)

initial investigations reveal that the terminus of the glacier rose upwards almost 61 m creating wide-edged crevices [4] and forward movement was also remarkable as compared to its previous typical position of July, 2018. In three and a half months starting from August 15, 2018, debris-covered glacial ice moved upward after hitting the nearby mountain and downward at the rate of ~ 9 m/day from higher elevation between April-August, 2018. This movement is indicated with up-arrows in the picture taken on August 15, 2018. During a second visit in April, 2019 it was observed that the surge rate had decreased from ~ 9 m/day to ~ 6 m/day. However, glacial ice material at the upper portion of glacier termini (indicated by up-arrow) damaged nearby vegetation and other infrastructure (e.g. water tank, melt water path) shown in thepicture taken on November 29, 2018. Until April 25, 2019 the termini were away from the bridge used to pass the water pipe to transport potable stream-water but came very close by June 05, 2019. On June 23, 2019 surrounding areas were damaged due to the sudden increased release of seepage of blocked melt water from the ice-dammed glacier lake.

According to a local hunter, the forward movement of Shishper glacier termini started in April, 2018 but the upward rise in June, 2018 escalated due to the backward dynamism resulting from the glacier's head-on collision with the neighboring mountain (Hachindar) to the southwest. Thousands of vertical crevices were created at lower elevations of the Shishper glacier terminus.

4.3 Spatio-temporal extent of sudden surge in Shishper glacier termini

As shown in the map (Fig. 7), total area of the Shishper glacier terminus in June, 2019 was 1.77 km^2. By December, 2019 this area expanded to 2.01 km^2 and 2.82 km^2 by May, 2019. This represents a total area increase of 88% over the 12-months of the study period. With an increase in the terminus of Shishper glacier, the extent of ice-dammed lake increased as well posing serious threat to downstream infrastructure. Results of hypsometric (ratio between glacial ice area and elevation) trend analysis of Shishper glacier termini from June, 2018 to May, 2019 are presented in Fig. 8. For reliability of results pertaining to

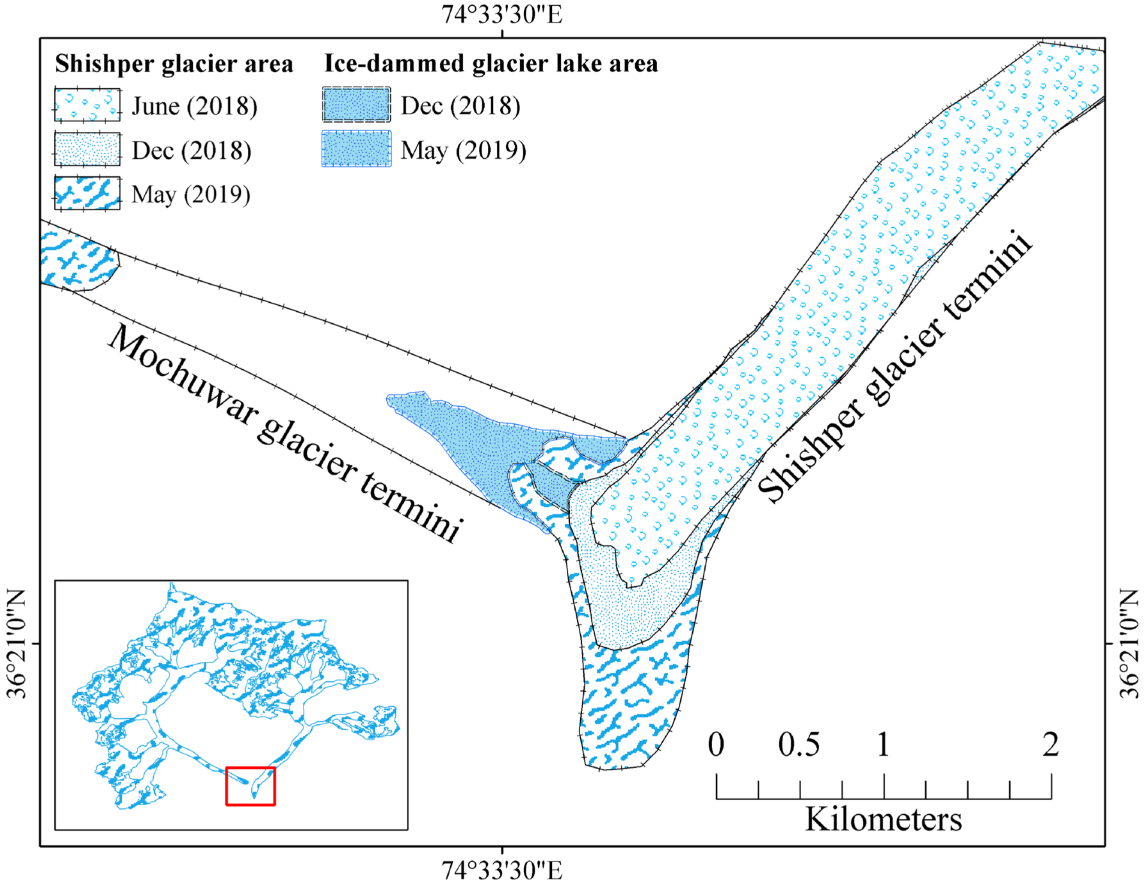


Fig. 7 Geographic map of month-wise advancing of Shishper glacier termini downwards (lower elevations) and ice-dammed glacier lake upwards (higher elevations) for the months December, 2018, June, 2018 and May, 2018, along with their corresponding area change (graph)

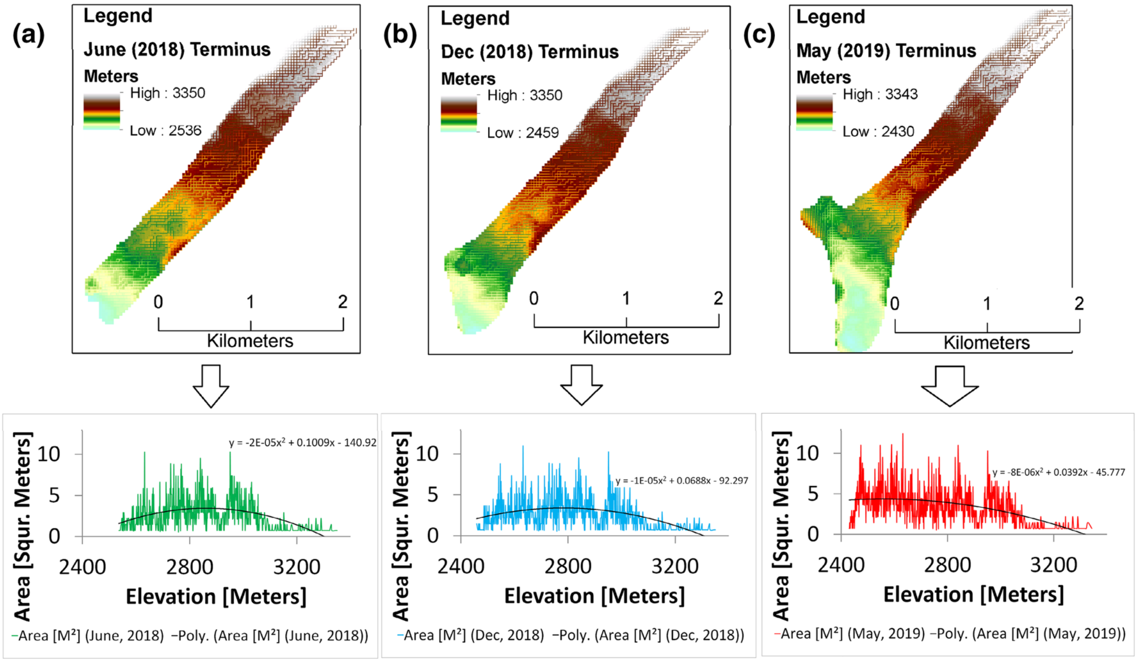


Fig. 8 Spatio-temporal hypsometric changes in the extent of debris-covered glacial ice area covered by Shishper glacier termini from June, 2018 to May, 2019. Map and corresponding graph for different months of the years: June, 2018 (**a**), December, 2018 (**b**) and May, 2019 (**c**)

surges, we present histograms of hypsometric curves for each month in Fig. 8a (June, 2018), Fig. 8b (December, 2018) and Fig. 8c (May, 2019). The fluctuation in the surge area is represented by polynomial trend lines for these months. Initially, rapid growth in the terminus is observed between elevations 2,600 to 2,500 m, but a relatively modest increase between 2500 and 2400 m.

Digital images of the extent of ice-dammed glacier lake and Shishper glacier termini taken on May 15, 2019 by Sher Khan are presented in Fig. 9. The snout of Shishper

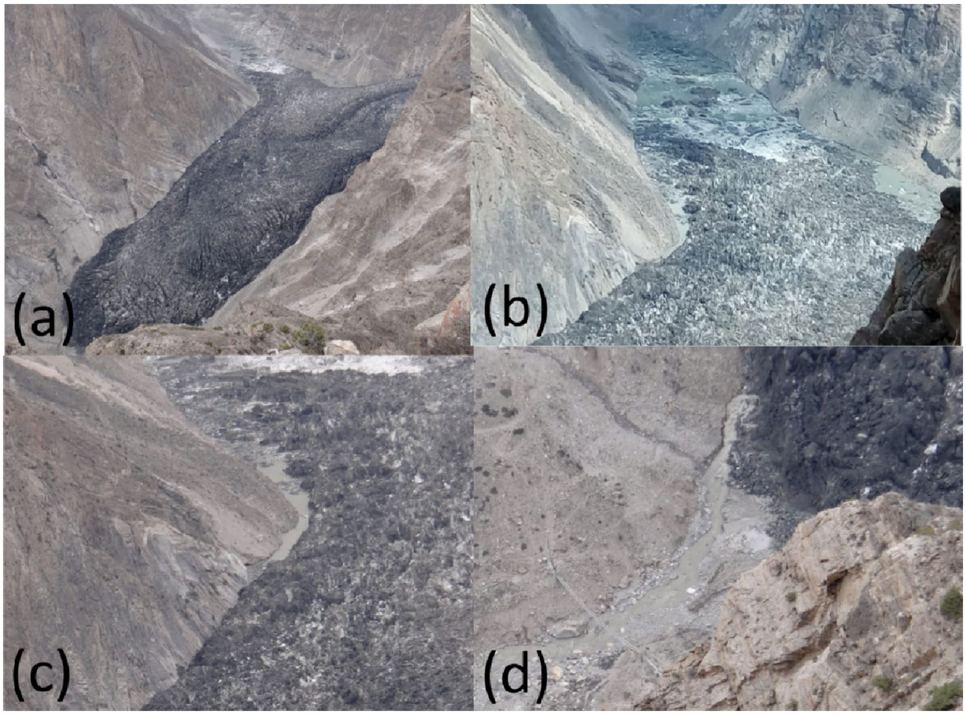


Fig. 9 Digital images of the extent of ice-dammed glacier lake and Shishper glacier termini taken on May 15, 2019 (source: Sher Khan). Snout of Shishper glacier covered by debris-covered ice (**a**) debris-covered floating ice broken from surging Shishper glacier on ice-dammed glacier lake extending to the west covering Mochuwar glacier moraine (**b**) blockage of river flow at the confluence (**c**) discharge of melt water beneath the surging glacier as seepage and position of pedestrian bridge made to pass potable water pipe from nearby stream (**d**)

glacier covered by debris-covered ice is depicted in Fig. 9a. Debris-covered floating ice broken from surging Shishper glacier on ice-dammed glacier lake extending to the west covering Mochuwar glacier moraine is shown in Fig. 9b. Blockage of river flow at the confluence of Shishper and Mochuwar glaciers is presented in Fig. 9c. Discharge of melt water beneath the surging glacier as seepage and position of pedestrian bridge made to pass potable water-pipe from nearby stream is depicted in Fig. 9d.

4.4 Ice-dammed glacial lake size, volume and discharge

The smallest and largest glacial lakes in Indus Basin are 0.003 km^2 and 5.2 km^2 respectively, and ice-dammed glacier lakes comprise only 0.1% of the total glacier lakes [22]. The newly formed Shishper glacier ice dammed lake was 0.04 km^2 in December, 2018. However, the lake area increased with passage of time from December 2018 onwards as shown in Fig. 10. Right after the sudden surging started in May, 2018, we found that no lake existed around the confluence of Shishper and Mochuwar glaciers until December 2018. However, in mid-December, 2018, a small-sized (~ 40 m^2) lake appeared within the Mochuwar glacier moraine, as compared to 0.057 km^2 estimated by Shah et al. [35] in the month of January, 2019. Gradually, the covered area of the newly formed Shishper Lake expanded from 0.04 km^2 (recorded for December, 2018) to 0.24 km^2 in May, 2019 representing a total area increase of 600% over 6 months. With an increasing trend in the extent of glacier lake area, water accumulation increased as well. The average depth of the lake is estimated to be 168.25 m covering a surface volume of 71, 542 m^3 and total volume of 39.5 million m^3. Relationship between Shishper glacier terminus advances and water-discharge from the confluence of Shishper and Mochuwar glaciers is shown in Fig. 11. The y-axis of the graph shows Shishper glacier terminus advances and irregular discharge of melt water from the blockage from April, 2018 to June, 2019. The video taken from the helicopter and shown by FOCUS (a local Aga Khan affiliated NGO) during a briefing at the Regional Council shows that the glacier ice dammed lake burst during daytime releasing thousands of cubic meters of melt water. Karim Dad, a local inhabitant, said "The Lake has completely drained out through multiple glacier crevasses and only icebergs can be seen in its bed. According to FOCUS at peak point ± 3000 m^3 of water discharged but it reduced to ± 2000 m^3 this morning after more than 24 h. By this evening it has further reduced".

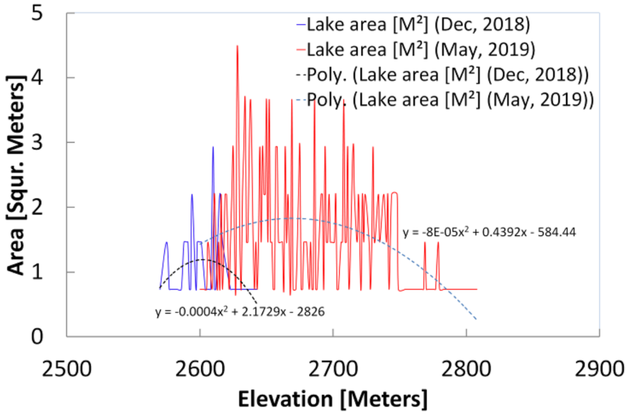


Fig. 10 Spatio-temporal movement and extent of ice-dammed glacial lake for the month December, 2018 and May, 2019

4.5 Water accumulation and discharge

Substantial accumulated-water discharge is observed between June 22–23, 2019 at Hassanabad watercourse (*Nullah*) from the ice-dammed glacial lake formed at the confluence of the surging Shishper Glacier and the receding Mochuwar glacier. The water discharge from the sub-glacier-surface reduced the accumulated-water to trivial quantity thereby reducing the potential risk of floods damaging downstream populations. Subsequently, the termini of the surging Shisper glacier receded. Although some of the recently made retaining walls (Fig. 12a) along the Hassanabad watercourse reduced the impact of water flow, mud-sliding (Fig. 12b) continued in the areas due to missing retaining walls or insufficient mitigation

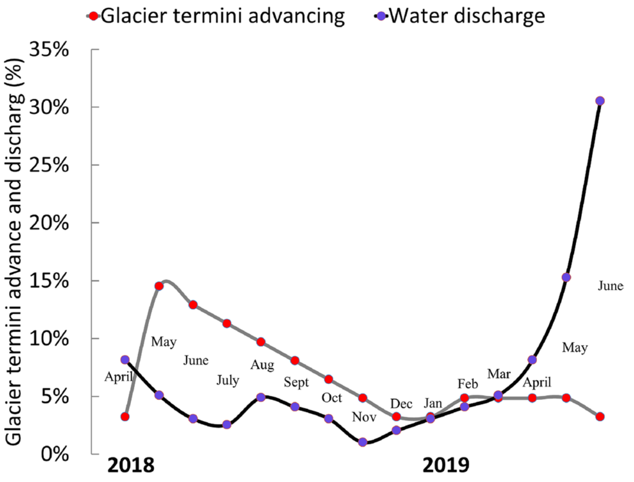


Fig. 11 Shishper glacier terminus advances and water-discharge from the confluence of Shishper and Mochuwar glaciers for 15 months based on information received from Water and Power Development Authority (WAPDA) officials. Sudden release of flush-muddy seepage-water depicting an irregular discharge of melt water from blockage between April, 2018 and June, 2019

Fig. 12 Pictures of damages to downstream infrastructure taken on June 23, 2019, due to sudden release of flush-muddy seepage-water discharged from the ice-dammed Shishper glacier lake. The recently made mitigation walls on both sides of the gorge to reduce the impact of ice-dammed glacier flood (**a**) outburst flood hitting the Karakoram Highway (connecting Pakistan with China) (**b**, **c**) damages done to forest on both sides of gorge (**d**)

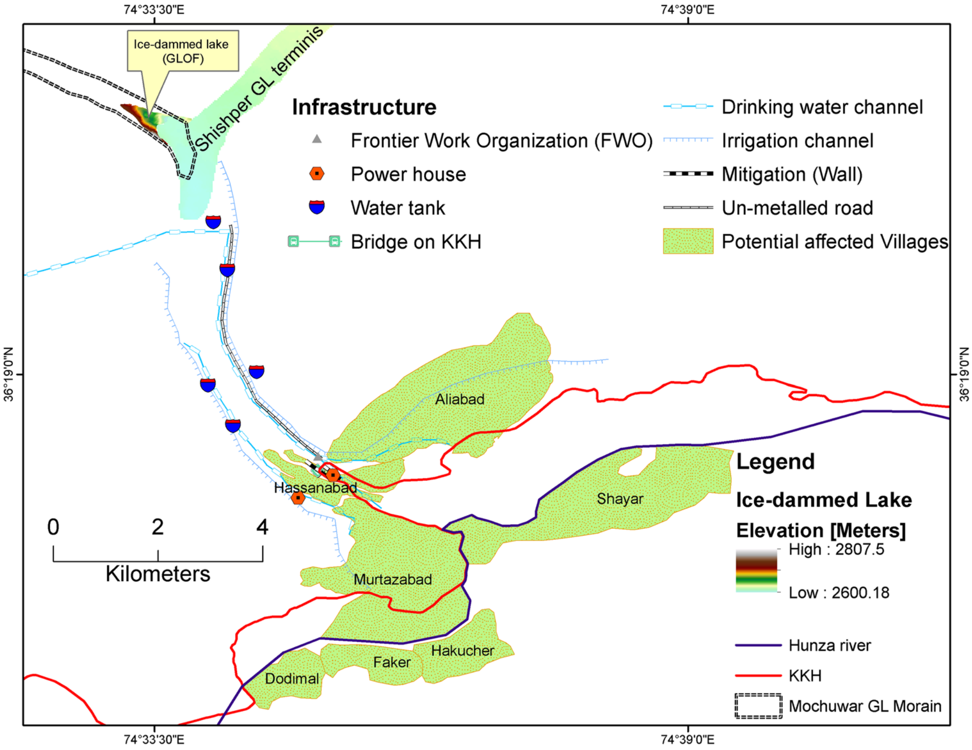


Fig. 13 Map of the public and private infrastructure (e.g. FWO office, power house, water tanks, bridge on KKH, drinking and irrigation water channels, mitigation walls and un-mettled roads exposed to a potential ice-dammed glacier lake

measures. However, the flow of discharged water due to the steepness of watercourse elevation partially damaged part of the KKH (Fig. 12c) and neighbored shrubs / forest (Fig. 12d).

4.6 Susceptibility profile of infrastructure exposed to ice-dammed lake

There are seven villages with around 15,000 inhabitants, three bridges, two hydropower plants, five water tanks, two drinking water channels for three villages and two irrigation channels in the upstream area of Shishper basin that could be affected by Shishper ice-dammed glacier lake outburst flooding (Fig. 13). Of these, three settlements (Hassanabad, Murtazaabad and Hakucher of Nagar district), two bridges (one on KKH and one connecting KKH with several villages of Nagar) and two hydropower plants (one under-construction and one already installed) lie under the direct stream flow gorge close to the Hunza river and possibly are at high risk. However, in this case study, a comprehensive modelling could not be undertaken to fix the exact risk-level. Up until the last reporting in April, 2019, an irrigation channel famously known as Hassanabad *Nullah*, which provides melt water to Aliabad village (~ 10,000 inhabitants), Hyderabad village (~ 4,000 inhabitants) and adjacent settlements, a newly made water tank for an under-construction water channel for hydropower plant and a suspension bridge were already damaged by this sudden surge of Shishper glacier.

The total expected worth of natural and man-made property prone to possible danger from Shishper ice-dammed glacier lake in the Hunza valley ranges from US$ 10 million to US$ 15 million, which is high compared to the assessed property losses in the 1905 flooding from the same outburst. The greater worth is partially because of considerable enhancement of costly infrastructure—including a bridge on KKH made in 1986, hydropower plants installed after 1980s, drinking water channels in 2005, new buildings for increased population, Hassanabad irrigation channel in 1994 and a floor mill in 2010. Expected damage cost in 1905 was based only on tangible loss of agricultural land without infrastructure.

5 Discussion

GLOFs are not a new phenomenon in the Karakoram Himalaya. This case study deals with a newly formed ice-dammed glacier lake in the Western Karakoram. Firstly, it is a special case because no evidence of the formation of an ice-dammed lake due to earlier surges is reported. Secondly, although, a list of surge-type largest glaciers of the Karakoram was provided by Hewitt [15], Shishper glacier was unnoticed due to its medium size and length. The current sudden advances in Shishper glacier terminus are considered to have a potential impact on the livelihood of downstream mountain communities, which are under risk from potential upsurge flooding linked with glacier hydrological variations and from ice-dammed lake flooding. The unusual surging of Shishper glacier has created a high degree of uncertainty among the inhabitants mainly due to speculations based on limited or lack of scientific / remote sensing data and future projections pertaining to the extent and implications of flooding. Although a number of local and international reports in newspapers (e.g. DAWN, the NEWS, Gulf News, Pamir Times, etc.) highlighted the implications of the surging phenomena, to what extent, in quantifiable terms, this surge started and continued was not known. Therefore, it was imperative to measure the current state and extent of the Shishper and Mochuwar glacier terminus and the volume of the newly formed glacier lake.

This study used a method based on a combination of space (remote sensing), ground observations and informal interviews to reconstruct spatio-temporal glacier termini and lake extent, hypsometries, and accumulated melt water in the lake. Ground observations were used to validate results of satellite imagery. Inclusion of community-derived information about glacier surging and lake extent was used to validate satellite imagery influenced by shadows of neighboring mountains. Furthermore, an attempt has been made to relate vertical and horizontal climatic regimes of Shishper glacier with its hypsometries because both are highly correlated with the ELA, accumulation, ablation and avalanche nourishment. With current insufficient mitigation plans and resources, it is not possible to completely avoid damages caused by the glacier flooding. Therefore increased efforts and more comprehensive contingency plans must be the top priority of concerned agencies for the rehabilitation of the inhabitants and infrastructure in case of a potential GLOF in the future.

6 Conclusion

The current unusual surging of Shishper glacier termini is responsible for the formation of ice-dammed glacier lake twice in the last 2 years. The fluctuation in the extent and geographic settings of Shishper glacier termini and this lake is an indication of the potential high-level risk to downstream mountain communities in terms of their lives, properties, and infrastructure. Unlike earlier anticipations, ~ 2 km long termini of the surging Shishper glacier significantly controlled water discharge devoid of triggering significant damage. Normally in the summers, only ~ 1,52,910–1,83,493 m^3/hr melt waster is reported to be discharged. However, 4, 07,762 m^3/hr melt water was discharged due to the surging Shishper glacier and the newly formed ice dammed Glacier Lake. If technically more advanced water discharge gauges are not installed at Hassnabad Nullah (watercourse), the downstream community would face the adverse effects of sudden release of melt water, which is a vital component of the hydrological system. Shishper glacier basin is becoming a closed basin or is on the edge of being closed as its water flow sometimes does not reach the Hunza River in winter.

High precipitation in the winter of 2018 and subsequent accumulation of snow on higher altitudes above 5,141 m and forcing may be some of the factors contributing to unusual advancing and subsequent formation of the an ice-dammed glacier lake. The current surge of the Shishper glacier can be characterized as type-I as it involves an in-built unsteadiness without any regular intervals due to an unknown mechanism producing very high movement of debris-covered glacial ice and sediment.

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Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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