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The January 2018 to September 2019 surge of Shisper glacier, Pakistan, detected from remote sensing observations

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Running Head: Surge of Shisper Glacier from remote sensing observations

Abstract

This study analysed the actively surging Shisper Glacier in the Karakoram region of Pakistan using earth observation data from Landsat 8 OLI and Planet images. Changes in the surface glacier velocity, supraglacial moraines and debris cover were assessed using Landsat 8 data at monthly time-steps from January 2018 to May 2019. High resolution data from Planet Labs was used to precisely detect the snout advance and ice-dammed lake expansion. Downstream cross-section profiles of the valley were generated using a moderate resolution digital elevation model to assess the inundation in the event of rapid ice-dammed lake drainage. Correlation Image Analysis Software working on the principle of normalized cross-correlation was used to generate time series monthly surface velocity profiles for Shisper Glacier. Manual digitization at 1:30000 scale was used to delineate supraglacial moraines and supraglacial debris cover. The glacier surface velocity profiles indicate that the ablation zone of the glacier continues to be in an active surge phase resulting in advance of the snout and expansion of the ice-dammed lake. Surface glacier velocities are as high as 48 m d^{-1}. Between 18 December 2018 and 8 May 2019, the glacier snout advanced at ~6 m d^{-1} with a total overall advance of 860 m. The lake formed due to damming of outflow stream from Mochowar Glacier expanded to its maximum area (29.69 ha) in May 2019 before drainage started on 23 June 2019. Our estimates indicate that the peak discharge in case of rapid drainage could vary between 5033 m^3s^{-1} and 6167 m^3s^{-1} and potentially affect infrastructure downstream.

Keywords: Shisper Glacier; Glacier surge; Karakoram; Glacier velocity; Remote sensing; Ice-dammed lake; GLOF hazard

1. Introduction

Glacier surges are characterised by flow instabilities where a glacier can advance very rapidly (10-100 times faster than normal) in a short time period (lasting few months to few years). This phenomenon has been reported from across the globe, for example, the Andes of Argentina, Alaska, High Mountain Asia (Karakoram and Pamir), Patagonia, Svalbard and Greenland (Hewitt, 1998; Sevestre and Benn, 2015; Yasuda and Furuya, 2015). Surge-type glaciers undergo a short-lived active phase characterized by flow instabilities, and a quiescent/stable phase that usually lasts for a decade or more (Meier and Post, 1969). Although glacier surges in the Karakoram remain poorly understood (Hewitt, 2005), velocities associated with surge-type glaciers increase by ~200% during the active phase (Hewitt, 1969; Jiskoot, 2011). However, studies indicate that the majority of the surge-type glaciers are often associated with ‘feeder’ tributaries and are 12-25 km long (Hewitt, 1969, 2007). Whereas dynamics of mountain glaciers has been extensively used to extract climate signals (Oerlemans, 2005; Banerjee and Azam, 2016) but owing to the anomalous behaviour of surging glaciers any attempt of drawing (paleo)climate inferences from such glaciers would be grossly misleading in light of current global climate discussion.

Karakoram glacier surges can occur at any time of year (Quincey et al., 2015). While some surges build-up extremely fast, others tend to grow gradually over time often resulting in substantial advance of the glacier snout (Kick, 1958; Gardner and Hewitt, 1990). The glacier surges in Karakoram could be either triggered by changes in thermal regimes (Hewitt, 2007) or changes in subglacial hydrological regimes (Copland et al., 2011; Mayer et al., 2011). While some studies indicate that glacier surges in the Karakoram are triggered by an interplay of thermal and hydrological conditions (Quincey et al., 2015), others suggest that the glacier surges could be controlled by landscape topographic (Lovell et al., 2018) and geomorphic characteristics (Paul, 2019).

The active surge phase at times blocks the path of rivers resulting in the formation of ice-dammed lakes (Mason, 1935; Hewitt, 1969; Hewitt and Liu, 2010) and also threatening life and key infrastructure like roads and bridges (Richardson and Reynolds, 2000; Ding et al., 2018). For instance, Steiner et al. (2018) reported on the surge of Khurdopin Glacier where an ice-dammed lake formed as a result of blockage of a tributary river, posing a threat to the communities and infrastructure downstream in case of an outburst. Similarly, Kääb et al. (2018) reported on a massive collapse of two adjacent glaciers in Tibet between July and September 2016 that triggered two huge avalanches resulting in 9 fatalities besides affecting livestock and infrastructure (Tian et al., 2017). Likewise, a lake outburst flood was triggered by surging of Northern Inylchek Glacier located in Central Tian Shan in 1996 (Häusler et al., 2016).

Although glaciers in Karakoram have been reported to be either gaining mass or stable (Gardelle et al., 2013; Bolch et al., 2017) there is a large body of recent scientific literature that reports actively surging glaciers in the Karakoram (Paul, 2015; Bhambri et al., 2017; Rashid et al., 2018; Singh et al., 2018). Keeping this in view, the current study characterizes the ongoing surge of Shisper Glacier using moderate and high resolution earth observation data. The study uses Landsat 8 OLI from 20 March 2018 to 16 March 2019 to generate surface velocity profiles, map the debris cover changes and delineate supraglacial moraines for Shisper Glacier. High resolution Cubesat images have been used to: (a) track changes in the snout position, and (b) monitor lake expansion caused by damming of the tributary stream originating from the neighbouring Mochowar Glacier. Stream profiles and potential peak discharge in case of lake outburst were generated to better understand the inundation and vulnerability of infrastructure downstream of the glacier snout.

2. Study Area

This article aims to document and characterize the currently surging Shisper glacier, located in Hunza valley, Northern Pakistan (**Figure 1**). Shisper is a 16.5 km long surge-type glacier (Shah et al., 2019), located in the Karakoram region (Lat: 36.35-36.48° N; 74.57-74.61° E) in Hunza valley, Pakistan, spread over an area of 26 km^2. Nestled between steep snow-covered mountains (mean slope 37°, highest slope 75°) the glacier is fed by both winter snow accumulation and snow avalanches. The elevation of the glacier varies between 2509 m asl and 7234 m asl. The peaks feeding respectively into Mochowar and Shisper glacier reach up to ~7700 m asl and ~7000 m asl. The transient snowline at the end of ablation season, considered to represent the equilibrium line altitude (ELA) of the glacier lies at 4568 m asl for 2015. Meltwaters from Shisper and the neighbouring Mochowar glacier form Hassanabad *Nallah* feeding into the Hunza River. The first report of surge of erstwhile Hassanabad glacier (Shisper and Mochowar glacier together) dates back to 1893-95 during which the glacier advanced by ~10 km in a span of just 75 days (Hayden, 1907). Hassanabad, a small village lying at an elevation of 2130 m asl is situated 5 km downstream of the snout of Shisper Glacier, and could be affected by floods if there is rapid drainage of the ice-dammed lake formed as a result of the surge. The Karakoram Highway, an important road link that connects Pakistan with China, passes through the area. Other key infrastructure includes Hassanabad Power Complex with a power generation capacity of 1200 KW and neighbouring villages further downstream (Shah et al., 2019). The mean annual temperature is 11°C while the region receives annual precipitation of 125 mm (https://en.climate-data.org/asia/pakistan/gilgit-baltistan/aliabad-50666/).

3. Datasets and Methods

3.1. Datasets

A repository of time series optical satellite data, panchromatic band of Landsat 8 OLI with a spatial resolution of 15 m, at nearly monthly time-step (January 2018-May 2019) were used for velocity estimation, debris cover mapping and delineation of supraglacial moraines (Details: Section 3.1, 3.2). The Landsat 8 OLI data did not need any geometric correction since it comes as an orthorectified product. Additionally, high resolution data (spatial resolution 3 m) acquired from Planet Cubesat constellation (Doves) from Planet labs (Planet 2017) with a spatial resolution of 3 m at monthly time-step (January 2018-September 2019) for the lower ablation region was used to precisely track the advance of the snout and the development of an ice-dammed lake formed due to blockage of a tributary of Hassanabad *Nallah* from neighbouring Mochowar Glacier. Additional details about Planet images have been described in greater detail in Kääb et al. (2019). The 30 m SRTM DEM was used to delineate the vulnerable areas in case of ice-dammed lake outburst. The complete details of the datasets used in this study are provided in **Table 1**.

3.2. Velocity

The feature tracking method based on comparison of consecutive monthly satellite image pairs was used to generate glacier-wide surface velocity profiles. For evaluating the surface velocity of Shisper Glacier, Correlation Image Analysis System (CIAS) algorithm based on principle of normalized cross-correlation (NCC) was used to estimate surface velocity of Shisper Glacier between different months (Kääb and Vollmer, 2000). This method has been widely used for assessing glacier velocities across the globe (Vollmer, 1999; Kääb, 2005; Heid and Kääb, 2012; Bhattacharya et al., 2016; Jawak et al., 2018; Bhutiyani and Mahto, 2018). The accuracy of this method is 1 pixel; equivalent to 15 m spatial resolution for Landsat Panchromatic data (Kääb and Vollmer, 2000).

3.2. Mapping features in glaciated terrain

Debris cover and supraglacial moraines were mapped from Landsat 8 OLI data using on-screen digitization in a GIS environment at 1:25,000 scale at monthly intervals to capture changes caused by the surge of Shisper Glacier. We did not apply any atmospheric correction on Landsat 8 OLI data, however, few image enhancement techniques like contrast stretch and histogram equalization were applied to make the glacier features more conspicuous (Bolch et al., 2010; Lee et al. 2013). Additionally, high resolution (3 m) images from Planet Labs were used to track snout advance and development of an associated ice-dammed lake at 1:2000 scale. The uncertainty related to the advance in glacier snout (E_{AD}) can be expressed as:

$$E_{AD} = \sqrt{\lambda_1^2 + \lambda_2^2} + \varepsilon \qquad (1)$$

where λ_1 and λ_2 represent the spatial resolution of images between two time periods and ε is error in georeferencing. Since the Planet imageries with a spatial resolution of 3m come as orthorectified georeferenced product, ε is 0. The uncertainty of change in glacier snout comes out to be ~4 m.

Infrastructure located 5 km downstream with respect to the snout of Shisper Glacier was also mapped at 1:2000 scale to get firsthand information about the number and distribution of settlements in the area. Manual digitization was preferred, keeping in view its advantages in delineation of geomorphic elements in a topographically complex glaciated landscape where shadows/clouds often pose a challenge problem in the interpretation of satellite image (Rashid and Abdullah, 2016). This was done since automated approaches are not very robust in capturing all the landscape elements in Himalayan terrain (Rashid et al., 2017).

3.3. Estimation of peak discharge

The volume of water in the ice-dammed lake was estimated using two volume-area scaling approaches proposed respectively by Evans et al. (1986) and Huggel et al. (2002) as:

$$V = 0.035 \times A^{1.5} \quad (2)$$

$$V = 0.104 \times A^{1.42} \quad (3)$$

where V is volume of proglacial lake (m^3) and A is lake area (m^2),

These methods of volume estimation of ice-dammed and moraine-dammed lakes have been widely tested in the Himalayas (Cook and Quincey, 2015; Rashid and Majeed, 2018) besides Western Canada () and the Swiss Alps () respectively. Another approach for estimation of mean depth of dammed lake in the Indian Himalaya proposed by Patel et al. (2017) was also used to estimate volume of water in ice-dammed lake associated with Shisper Glacier surge.

$$MD = 4 \times 10^{-5} \times A + 5.0564 \quad (4)$$

$$V = A \times MD \quad (5)$$

where MD is mean depth of lake (m)

Volume estimate equations (2), (3) and (5) were used for quantifying the peak discharge in case of outburst as suggested by Huggel et al. (2002) as:

$$Q_{\max} = 0.00077 \times V^{1.017} \quad ...(6)$$

where Qmax is peak discharge in case of a lake outburst (m^3s^{-1}).

3.4. Delineation of flood prone area

The flood prone area was delineated by generating four valley cross-section profiles starting from the Hassanabad village up to the culmination of Hassanabad *Nallah* in Hunza river using 3D Analyst module of ESRI's Arc Map 10.2. These cross sections were drawn in such a manner so that they can accommodate peak discharge in case of an outburst flood. This analysis provided an insight into the area and associated infrastructure that could be potentially affected by the outburst flood if the lake was to drain rapidly.

4. Results

4.1. Velocity Changes

Although Shisper Glacier is believed to have started surging in June 2018 (Shah et al., 2019), the analysis of daily mean surface velocities using Landsat 8 OLI data range from 3.7-27 m d^{-1} while the maximum velocities range from 13.5-47.76 m d^{-1} (**Figure 2**). Analysis of surface velocity profiles of Shisper indicate that the surge was restricted to the accumulation zone between March 2018 and August 2018 (**Figure 3a-f**), however, the surge wave started moving down the glacier trunk in subsequent months between August and October (Figure 2e,f). The surge affected the entire glacier between November and December, with mean velocities of 27 m d^{-1} (**Figure 3g,h**). The surface velocity of the glacier decelerated to 8 m d^{-1} and 7 m d^{-1} for December 2018-January 2019 and January-February 2019 periods respectively (**Figure 3i,j**). Although the velocity profile for February-March 2019 indicates mean velocities of 9 m d^{-1}, the maximum velocities reach 48 m d^{-1} predominantly in the zone of ablation of the glacier (**Figure 3k**). The mean surface velocity of the glacier reached 20 m d^{-1} between March and May 2019 (**Figure 3l**). The mean glacier velocities in the ablation and accumulation zone (**Table 2**) also indicate that the surge in Shisper started in the accumulation zone and gradually transferred to the ablation zone. The velocity profiles in the ablation (24-55 m d^{-1}) and accumulation zones (13-28 m d^{-1}) since January 2019 clearly indicate that the glacier surge is more pronounced in the ablation zone.

4.2. Changes in debris cover and supraglacial moraines

Changes in the debris cover and supraglacial moraines were analysed using nine Landsat 8 OLI scenes acquired between January 2018 and April 2019. To reduce uncertainties relating to snow masking, five completely snow-free images were chosen to assess the debris cover dynamics on Shisper Glacier. The supraglacial debris is fed to the glacier surface from surrounding headwalls which continuously erode due to frost-shattering (Hewitt, 2014). Debris cover on Shisper varied between 43.39-71.52% (**Figure 4**). The debris cover showed an increase from 43-71% between June 2018 and September 2018 primarily due to the snowmelt in ablation zone during summer. However, the debris cover started to decrease due to the onset of winter and snowfall in the higher reaches of glacier from October 2018. The decrease in debris cover during October 2018 could also be attributed to the accelerated flux of ice/snow accumulation zone to the ablation zone driven by changes in surface velocity of Shisper glacier. Distinct changes were observed in the supraglacial moraine features during the analysis period as indicated by the presence, formation and disappearance of looped and folded moraines since the glacier is in active surge phase (**Figure 5**). The formation and disappearance of supraglacial moraines on Shisper result due to anomalously high surface velocities associated with extremely dynamic ice-flux. The moraines appear to start forming in April 2018 (**Figure 5b**) and are identifiable on the images untill October 2018. However, noticeable changes manifested as breaks in moraine structures were observed below the ELA of the glacier. The supraglacial moraines start disappearing from 2019 possibly due to the rise in mean velocities in the ablation zone of Shisper Glacier (Wilson et al., 2016) that result in enhanced ice flux overriding the moraines. The cumulative moraine length showed an increase from March 2018 to July 2018 (Table 3) indicative of snow/ice melt in the ablation season. Between July 2018 and August 2018 the moraine length decreased indicating an anomalous behaviour. Between August 2018 and September 2018 the moraine length again increased before again decreasing in September 2018-October 2018. The decrease in moraine length between February 2019 and April 2019 again showed a decrease. The dynamics in the number of supraglacial moraine features is also indicative of deviation from the normal behaviour of Shisper glacier.

4.3. Snout Fluctuations

The snout of the glacier advanced by 1047 m (±4m) at an average rate of 1.8 m d^{-1} between February 2018 and September 2019 as assessed from high resolution Rapid Eye data provided by Planet Labs (**Figure 6, 7**). Since Planet images have been used for tracking the snout advance of Shisper Glacier, the uncertainty of snout change is always ±4m. The snout slightly advanced by 17.55 m at the rate of ~0.19 m d^{-1} between March and May 2018 and started rapidly advancing thereafter. The snout advance between February-March, March-April and April-May 2018 respectively was 17.55, 12.6 m and 5.9 m. The glacier snout advanced by another 16.9 m during May-June 2018. The glacier snout showed a remarkable advance of 63.54 m between 18 June and 16 July 2018 which amounts to about 2.27 m advance per day. A consistent snout advance was observed between August and October 2018. The snout advanced very slowly by 9.35 m, 8.07 m and 7.31 m during July-August, August-September and September-October 2018 periods respectively. The snout advanced by another 20 m during October-November 2018. The snout advanced at 5 m d^{-1} between 20 November and 18 December 2018; an overall advance of 140 m. The glacier snout advanced more pronouncedly at 4.9 m d^{-1} between 18 December 2018 and 8 May 2019, however, this advance is not secular. The glacier advanced by 144.47 m (5.35 m d^{-1}), 400 m (6.78 m d^{-1}), 138 m (3.94 m d^{-1}), 65 m (2.32 m d^{-1}), 134 m (1.11 m d^{-1}) for December-January, January-March, March-April and April-May, May-September respectively.

4.4. Evolution of the ice-dammed lake

The snout advance of Shisper Glacier blocked the water stream originating from the adjacent Mochowar Glacier. This resulted in formation of an ice-dammed lake in November 2018, which expanded up to June 2019 (**Figure 8**). While the lake covered an area of 2.1 ha in November 2018 it expanded to 10.11 ha in December 2018. The lake areas for January, February and March 2019 were 15.79 ha, 21.16 ha and 26.49 ha respectively. The lake expanded to its highest area (29.69 ha) in May 2019. It is clear from **Figure 8h** that the water from the ice-dammed lake started draining out in June as indicated by shrinkage in lake area. The lake completely emptied by July 2019 (**Figure 8i**)

Based on area-volume scaling approaches in equation (1), (2) and (4) the lake water volume for the current lake was estimated at 5.66 million m^3, 6.14 million m^3 and 5.03 million m^3 respectively. The corresponding peak discharges as per equation (5) are 5680.06 m^3s^{-1}, 6167.41 m^3s^{-1} and 5033.04 m^3s^{-1} from the current ice-dammed lake. If it were to drain rapidly, this could pose flood risk to the population living in Hassanabad hamlet and adjacent areas. However, the lake drained quite steadily starting on 22 June 2019, damaging a part of Karakoram highway and adjacent river banks while Shisper Glacier continued to be in a state of surge.

4.5. Outburst flood prone area

We mapped the infrastructure of Hassanabad village located 5 km downstream of the present snout of Shisper Glacier. We delineated 360 buildings in the Hassanabad ravine, most of which are residential houses (**Figure 9**) with a population of 1500 people (https://www.pbs.gov.pk). Shah et al. (2019) also note there is an important bridge of the Karakoram highway, water tanks and a hydropower generating station in the area. The flood prone area was delineated by calculating the capacity of 5 cross sectional profiles across Hassanabad nallah based on peak discharge estimates of the ice-dammed lake (**Figure 10**).

The areas, 157 buildings, falling within the 5 delineated cross-sections that could be inundated if the ice-dammed lake drains rapidly (**Figure 11**). Keeping in view average occupancy of 4.16, the outburst could potentially pose a risk to ~654 people living in Hassanabad village. A higher resolution DEM procured from UAV or high resolution remote sensing platforms and a more sophisticated hydrological flood model would be required to precisely quantify the area at risk. Since the glacier is currently in an active state of surge we predict the formation of the ice-dammed lake again during the onset of winters owing to the freezing temperatures that may freeze the glacier bed. The water may get siphoned off again during the onset of summer later next year but the rate of release will depend on whether the glacier remains in the surge phase or not. Similar phenomena have been observed in surrounding glaciers in the region, the recent one being Kyagar glacier surge and formation of an ice-dammed lake (Veh et al., 2019).

5. Discussion

The reports pertaining to the surge of Shisper glacier date back to late nineteenth century (Hayden, 1907). Literature suggests that Shisper glacier and its adjoining Mochowar glacier were tributaries of a single erstwhile glacier-Hassanabad. Due to a 7 km retreat, the Hassanabad glacier fragmented into two glaciers-Shisper and Mochowar in 1954 (Paffen et al. 1956). The glaciers joined together in 1972 owing to the surge of Mochowar glacier (Bhambri et al. 2017). Shisper glacier surged again from 1972-1976 and 1993-2002 (Bhambri et al. 2019). The current surge of glacier started in early 2018 and continues till date suggesting that the glacier surges every 16 years since 1970s. The surging of Shisper glacier in 1970s and 1990s are indicative that the glacier remains in active phase for few years once it moves out of quiescent phase. This could be very important when it comes to establishing the recurrence interval of surges of individual glaciers.

While the Shisper Glacier started surging since early 2018, the surface velocity of the glacier reached to their maxima (~48 m d^{-1}) during October-December 2018 profiles of Shisper glacier, however, due to the onset of winter the glacier velocity decelerated appreciably. The rise in the surface velocities again between February--May 2019 could be possibly attributed to rise in temperatures from winter to spring that might have accelerated the melt processes (Björnsson, 1998) and lubricated the glacier bed (Copland et al., 2009). The velocity profiles suggest that the glacier is still in its active surge phase. Similar high velocity profiles have been reported for surging Hispar (Paul et al., 2017), Khurdopin (Steiner et al., 2018) and Kygar (Round et al., 2017) glaciers in the Karakoram region.

The inter-monthly variability in debris cover is indicative of actively surging glacier attributed to heterogeneity in the surface velocity of Shisper Glacier (Quincey et al., 2009; Gibson et al., 2017). The formation and degeneration of folded and looped moraines on the glacier surface are also indicative of the actively surging glacier (Meier and Post, 1969; Grant et al., 2009). The dynamics in the number of supraglacial moraine features and their total length across the analysis period also indicate that the glacier is in an active surge phase (Rashid et al., 2018).

Glacier surges often translate into rapid snout advances (Harrison et al., 2015). The snout of Shisper Glacier started advancing slowly (0.19 m d^{-1}) in early 2018 reaching up to 6 m d^{-1} (between November 2018 and May 2019). The snout advance again decreased to ~1m d^{-1} between May 2019 and September 2019. Similar high rates of snout advance have been recently reported in other surging glaciers of Karakoram region (Paul et al., 2017; Round et al., 2017; Steiner et al., 2018).

The ice-dammed lake formed due to blockage of stream originating from neighbouring Mochowar glacier reached its maximum area of 29.69 Ha in May 2019 . The empirical volume-area scaling approaches suggested that the peak discharge in case of lake burst would always be in excess of 5000 m^3s^{-1}. This data together with valley cross-section profiles suggested that the rapid drainage of the ice-dammed lake could pose a huge risk to the population (>650 people) and associated infrastructure (>150 buildings) downstream. It is worth remembering that the outburst flood of Chorabari Taal in Kedarnath that resulted in a peak discharge of 783 m^3 s^{-1} (Rao et al., 2014), seven times lower magnitude compared with the peak discharge estimated in this study, killed ~6000 people (Guha-Sapir et al., 2014) besides damaging 30 hydropower plants and many bridges in the area (Sati and Gahalaut, 2013). The lake however drained quietly later half of June without substantial damage although studies indicate that such ice-dammed lakes can result into destructive outburst floods (Hewitt and Liu, 2010). This indicates that empirical approaches of quantifying peak discharge of ice-dammed lakes resulting due to surging glaciers are not appropriate to quantify risk of such lakes to downstream population.

6. Conclusions

- The surge of Shisper Glacier between March 2018 and September 2019 was identified using Landsat 8 OLI and Planet imageries. At the peak of the surge, mean surface glacier velocities of Shisper reached 27 m d^{-1} between November 2018 and December 2018. Presently, the glacier surge is more active in the ablation zone as indicated by high surface velocities.
- The debris cover on Shisper Glacier varied between ~40% and ~70%. The formation and disappearance of supraglacial moraines on Shisper Glacier is controlled by surface velocities. Supraglacial moraines were characterized by contortion, indicating differential ice flux across the glacier surface during the active phase.
- Between March 2018 and September 2019 the snout of the glacier advanced by 1.047 km, resulting in the formation of an ice-dammed lake by blocking the meltwater

tributary emanating from neighbouring Mochowar Glacier. The glacier snout advanced at the highest rate of 6.78 m d^{-1} between February 2019 and March 2019 during the entire observation period.

- The lake expanded to ~30 ha, trapping a water volume between 5.03 million m^3 and 6.14 million m^3 with peak discharge potential of 5626 m^3s^{-1} and posing a potential flood risk to downstream population and infrastructure. However, the lake waters released steadily during June 2019 damaging a small portion of the Karakoram highway without damaging any infrastructure. This indicates that empirical approaches of quantifying peak discharge are not appropriate to quantify risk to population living downstream. There is, however, a likelihood that the currently active surging Shisper glacier may again result into the formation of an ice-dammed lake as winters arrive in the region.

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Figure Captions:

Figure 1. Location of the study area. Background: Landsat 8 OLI True Colour Composite image acquired on 10th July 2018.

Figure 2. Mean and maximum velocity (m d^{-1}) of Shisper glacier between March 2018 and May 2019. Red indicates 2018 while purple indicates 2019.

Figure 3. Glacier-wide surface velocity of Shisper between March 2018 and May 2019: (a) March-April 2018; (b) April-June, 2018; (c)June-July 2018; (d) July-August, 2018; (e) August-September 2018; (f) September-October, 2018; (g) October-November 2018; (h) November-December 2018; (i) December 2018-January 2019; (j) January-February 2019; (k) February-March 2019 and (l) March-May 2019.

Figure 4. Variability in debris cover of Shisper glacier: (a) June 2018; (b) July 2018; (c) August 2018 (d) September 2018 and (e) October 2018.

Figure 5. Supraglacier moraine dynamics: (a) March 2018; (b) April 2018; (c) June 2018; (d) July 2018; (e) August, 2018; (f) September 2018; (g) October 2018; (h) February 2019 and (i) April 2019.

Figure 6. Snout advance of Shisper glacier as assessed from Planet data: (a) Red-February, Blue grey-March, Blue-April and Green-May 2018; (b) Green-May, Purple-June 2018; (c) Purple-June, Cyan-July 2018; (d) Cyan-July, Red-August 2018; (e) Red-August, Yellow-September, Cyan-October, Green-November, and Orange-December 2018; (f) January 2019; (g) March 2019; (h) April 2019; (i) May 2019; (j) June 2019; (k) July 2019 and (l) Cyan-August, Purple-September 2019. Arrows indicate position of snout at the time of surge: Cyan-February 2018 and Red: Current snout position (September 2019).

Figure 7. Snout advance of Shisper Glacier February 2018 and September 2019. Red indicates 2018 while purple indicates 2019.

Figure 8. Ice-dammed lake expansion between November 2018 and July 2019: (a) November, 2018; (b) December 2018; (c) January 2019; (d) February 2019; (e) March 2019; (f) April 2019; (g) May 2019; (h) June 2019 and (i) July 2019.

Figure 9. Settlements along with valley cross-section delineated from high resolution satellite data.

Figure 10. Valley cross-section profiles for determining the potential to withhold outburst flood waters (a) CS1; (b) CS2; (c) CS3; (d) CS4 and (e) CS5.

Figure 11. Settlements potentially facing outburst flood risk.