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

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6	The January 2018 to September 2019 surge of Shisper glacier, Pakistan, detected from
7	remote sensing observations
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23	Running Head: Surge of Shisper Glacier from remote sensing observations
24	Abstract

25 This study analysed the actively surging Shisper Glacier in the Karakoram region of Pakistan 26 using earth observation data from Landsat 8 OLI and Planet images. Changes in the surface 27 glacier velocity, supraglacial moraines and debris cover were assessed using Landsat 8 data at 28 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 29 30 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. 31 32 Correlation Image Analysis Software working on the principle of normalized cross-33 correlation was used to generate time series monthly surface velocity profiles for Shisper 34 Glacier. Manual digitization at 1:30000 scale was used to delineate supraglacial moraines and 35 supraglacial debris cover. The glacier surface velocity profiles indicate that the ablation zone 36 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 37 18 December 2018 and 8 May 2019, the glacier snout advanced at ~6 m d⁻¹ with a total 38 39 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 40 41 started on 23 June 2019. Our estimates indicate that the peak discharge in case of rapid drainage could vary between 5033 m³s⁻¹ and 6167 m³s⁻¹ and potentially affect infrastructure 42 43 downstream.

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

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49 **1.** Introduction

50 Glacier surges are characterised by flow instabilities where a glacier can advance very rapidly 51 (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 52 53 Argentina, Alaska, High Mountain Asia (Karakoram and Pamir), Patagonia, Svalbard and Greenland (Hewitt, 1998; Sevestre and Benn, 2015; Yasuda and Furuya, 2015). Surge-type 54 55 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). 56 57 Although glacier surges in the Karakoram remain poorly understood (Hewitt, 2005), 58 velocities associated with surge-type glaciers increase by ~200% during the active phase 59 (Hewitt, 1969; Jiskoot, 2011). However, studies indicate that the majority of the surge-type 60 glaciers are often associated with 'feeder' tributaries and are 12-25 km long (Hewitt, 1969, 61 2007). Whereas dynamics of mountain glaciers has been extensively used to extract climate 62 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 63 64 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 65 66 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 67 68 surges in Karakoram could be either triggered by changes in thermal regimes (Hewitt, 2007) 69 or changes in subglacial hydrological regimes (Copland et al., 2011; Mayer et al., 2011). 70 While some studies indicate that glacier surges in the Karakoram are triggered by an interplay 71 of thermal and hydrological conditions (Quincey et al., 2015), others suggest that the glacier 72 surges could be controlled by landscape topographic (Lovell et al., 2018) and geomorphic characteristics (Paul, 2019). 73

74 The active surge phase at times blocks the path of rivers resulting in the formation of ice-75 dammed lakes (Mason, 1935; Hewitt, 1969; Hewitt and Liu, 2010) and also threatening life 76 and key infrastructure like roads and bridges (Richardson and Reynolds, 2000; Ding et al., 77 2018). For instance, Steiner et al. (2018) reported on the surge of Khurdopin Glacier where 78 an ice-dammed lake formed as a result of blockage of a tributary river, posing a threat to the 79 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 80 81 September 2016 that triggered two huge avalanches resulting in 9 fatalities besides affecting 82 livestock and infrastructure (Tian et al., 2017). Likewise, a lake outburst flood was triggered 83 by surging of Northern Inylchek Glacier located in Central Tian Shan in 1996 (Häusler et al., 84 2016).

85 Although glaciers in Karakoram have been reported to be either gaining mass or stable 86 (Gardelle et al., 2013; Bolch et al., 2017) there is a large body of recent scientific literature 87 that reports actively surging glaciers in the Karakoram (Paul, 2015; Bhambri et al., 2017; 88 Rashid et al., 2018; Singh et al., 2018). Keeping this in view, the current study characterizes 89 the ongoing surge of Shisper Glacier using moderate and high resolution earth observation 90 data. The study uses Landsat 8 OLI from 20 March 2018 to 16 March 2019 to generate 91 surface velocity profiles, map the debris cover changes and delineate supraglacial moraines 92 for Shisper Glacier. High resolution Cubesat images have been used to: (a) track changes in 93 the snout position, and (b) monitor lake expansion caused by damming of the tributary stream 94 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 95 96 vulnerability of infrastructure downstream of the glacier snout.

97

98 2. Study Area

100 This article aims to document and characterize the currently surging Shisper glacier, located 101 in Hunza valley, Northern Pakistan (Figure 1). Shisper is a 16.5 km long surge-type glacier 102 (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 km². Nestled between steep snow-covered 103 104 mountains (mean slope 37°, highest slope 75°) the glacier is fed by both winter snow 105 accumulation and snow avalanches. The elevation of the glacier varies between 2509 m asl 106 and 7234 m asl. The peaks feeding respectively into Mochowar and Shisper glacier reach up 107 to ~7700 m asl and ~7000 m asl. The transient snowline at the end of ablation season, 108 considered to represent the equilibrium line altitude (ELA) of the glacier lies at 4568 m asl 109 for 2015. Meltwaters from Shisper and the neighbouring Mochowar glacier form Hassanabad 110 Nallah feeding into the Hunza River. The first report of surge of erstwhile Hassanabad 111 glacier (Shisper and Mochowar glacier together) dates back to 1893-95 during which the 112 glacier advanced by ~10 km in a span of just 75 days (Hayden, 1907). Hassanabad, a small 113 village lying at an elevation of 2130 m asl is situated 5 km downstream of the snout of 114 Shisper Glacier, and could be affected by floods if there is rapid drainage of the ice-dammed 115 lake formed as a result of the surge. The Karakoram Highway, an important road link that 116 connects Pakistan with China, passes through the area. Other key infrastructure includes 117 Hassanabad Power Complex with a power generation capacity of 1200 KW and neighbouring 118 villages further downstream (Shah et al., 2019). The mean annual temperature is 11°C while 119 the region receives annual precipitation of 125 (https://en.climatemm 120 data.org/asia/pakistan/gilgit-baltistan/aliabad-50666/).

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123 **3.** Datasets and Methods

124 **3.1.** Datasets

125 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 126 127 for velocity estimation, debris cover mapping and delineation of supraglacial moraines 128 (Details: Section 3.1, 3.2). The Landsat 8 OLI data did not need any geometric correction 129 since it comes as an orthorectified product. Additionally, high resolution data (spatial 130 resolution 3 m) acquired from Planet Cubesat constellation (Doves) from Planet labs (Planet 131 2017) with a spatial resolution of 3 m at monthly time-step (January 2018-September 2019) 132 for the lower ablation region was used to precisely track the advance of the snout and the 133 development of an ice-dammed lake formed due to blockage of a tributary of Hassanabad 134 Nallah from neighbouring Mochowar Glacier. Additional details about Planet images have 135 been described in greater detail in Kääb et al. (2019). The 30 m SRTM DEM was used to 136 delineate the vulnerable areas in case of ice-dammed lake outburst. The complete details of 137 the datasets used in this study are provided in Table 1.

138

139 **3.2.** Velocity

140 The feature tracking method based on comparison of consecutive monthly satellite 141 image pairs was used to generate glacier-wide surface velocity profiles. For evaluating the 142 surface velocity of Shisper Glacier, Correlation Image Analysis System (CIAS) algorithm 143 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 144 145 has been widely used for assessing glacier velocities across the globe (Vollmer, 1999; Kääb, 146 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 147 148 for Landsat Panchromatic data (Kääb and Vollmer, 2000).

149

150 **3.2. Mapping features in glaciated terrain**

151 Debris cover and supraglacial moraines were mapped from Landsat 8 OLI data using 152 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 153 154 on Landsat 8 OLI data, however, few image enhancement techniques like contrast stretch and 155 histogram equalization were applied to make the glacier features more conspicuous (Bolch et 156 al., 2010; Lee et al. 2013). Additionally, high resolution (3 m) images from Planet Labs were 157 used to track snout advance and development of an associated ice-dammed lake at 1:2000 158 scale. The uncertainty related to the advance in glacier snout (E_{AD}) can be expressed as:

159
$$E_{AD} = \sqrt{\lambda_1^2 + \lambda_2^2} + \varepsilon$$
(1)

160 where λ_1 and λ_2 represent the spatial resolution of images between two time periods and ε is 161 error in georeferencing. Since the Planet imageries with a spatial resolution of 3m come as 162 orthorectified georeferenced product, ε is 0. The uncertainty of change in glacier snout comes 163 out to be ~4 m.

164 Infrastructure located 5 km downstream with respect to the snout of Shisper Glacier 165 was also mapped at 1:2000 scale to get firsthand information about the number and 166 distribution of settlements in the area. Manual digitization was preferred, keeping in view its 167 advantages in delineation of geomorphic elements in a topographically complex glaciated 168 landscape where shadows/clouds often pose a challenge problem in the interpretation of 169 satellite image (Rashid and Abdullah, 2016). This was done since automated approaches are 170 not very robust in capturing all the landscape elements in Himalayan terrain (Rashid et al., 171 2017).

173 **3.3.** Estimation of peak discharge

174 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:

176
$$V = 0.035 \times A^{1.5}$$
 (2)

177
$$V = 0.104 \times A^{1.42}$$
 (3)

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

- $185 \qquad V = A \times MD \tag{5}$
- 186 where MD is mean depth of lake (m)

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

189
$$Q_{\text{max}} = 0.00077 \times V^{1.017}$$
 ...(6)

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

191 **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 196 analysis provided an insight into the area and associated infrastructure that could be 197 potentially affected by the outburst flood if the lake was to drain rapidly.

198

199 **4. Results**

200 4.1. Velocity Changes

201 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 3.7-202 27 m d⁻¹ while the maximum velocities range from 13.5-47.76 m d⁻¹ (Figure 2). Analysis of 203 204 surface velocity profiles of Shisper indicate that the surge was restricted to the accumulation 205 zone between March 2018 and August 2018 (Figure 3a-f), however, the surge wave started 206 moving down the glacier trunk in subsequent months between August and October (Figure 207 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⁻¹ 208 and 7 m d⁻¹ for December 2018-January 2019 and January-February 2019 periods 209 210 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 211 of ablation of the glacier (Figure 3k). The mean surface velocity of the glacier reached 20 m 212 213 d⁻¹ between March and May 2019 (Figure 3I). The mean glacier velocities in the ablation and 214 accumulation zone (Table 2) also indicate that the surge in Shisper started in the 215 accumulation zone and gradually transferred to the ablation zone. The velocity profiles in the 216 ablation (24-55 m d⁻¹) and accumulation zones (13-28 m d⁻¹) since January 2019 clearly 217 indicate that the glacier surge is more pronounced in the ablation zone.

218

219 **4.2.** Changes in debris cover and supraglacial moraines

220 Changes in the debris cover and supraglacial moraines were analysed using nine Landsat 221 8 OLI scenes acquired between January 2018 and April 2019. To reduce uncertainties 222 relating to snow masking, five completely snow-free images were chosen to assess the debris 223 cover dynamics on Shisper Glacier. The supraglacial debris is fed to the glacier surface from 224 surrounding headwalls which continuously erode due to frost-shattering (Hewitt, 2014). 225 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 226 227 snowmelt in ablation zone during summer. However, the debris cover started to decrease due 228 to the onset of winter and snowfall in the higher reaches of glacier from October 2018. The 229 decrease in debris cover during October 2018 could also be attributed to the accelerated flux 230 of ice/snow accumulation zone to the ablation zone driven by changes in surface velocity of 231 Shisper glacier. Distinct changes were observed in the supraglacial moraine features during 232 the analysis period as indicated by the presence, formation and disappearance of looped and 233 folded moraines since the glacier is in active surge phase (Figure 5). The formation and 234 disappearance of supraglacial moraines on Shisper result due to anomalously high surface 235 velocities associated with extremely dynamic ice-flux. The moraines appear to start forming 236 in April 2018 (Figure 5b) and are identifiable on the images untill October 2018. However, 237 noticeable changes manifested as breaks in moraine structures were observed below the ELA 238 of the glacier. The supraglacial moraines start disappearing from 2019 possibly due to the rise 239 in mean velocities in the ablation zone of Shisper Glacier (Wilson et al., 2016) that result in 240 enhanced ice flux overriding the moraines. The cumulative moraine length showed an 241 increase from March 2018 to July 2018 (Table 3) indicative of snow/ice melt in the ablation 242 season. Between July 2018 and August 2018 the moraine length decreased indicating an 243 anomalous behaviour. Between August 2018 and September 2018 the moraine length again 244 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.

248

249 **4.3.** Snout Fluctuations

The snout of the glacier advanced by 1047 m (±4m) at an average rate of 1.8 m d⁻¹ 250 251 between February 2018 and September 2019 as assessed from high resolution Rapid Eye data 252 provided by Planet Labs (Figure 6, 7). Since Planet images have been used for tracking the 253 snout advance of Shisper Glacier, the uncertainty of snout change is always $\pm 4m$. The snout slightly advanced by 17.55 m at the rate of ~0.19 m d⁻¹ between March and May 2018 and 254 255 started rapidly advancing thereafter. The snout advance between February-March, March-256 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 257 258 advance of 63.54 m between 18 June and 16 July 2018 which amounts to about 2.27 m 259 advance per day. A consistent snout advance was observed between August and October 260 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 261 another 20 m during October-November 2018. The snout advanced at 5 m d⁻¹ between 20 262 November and 18 December 2018; an overall advance of 140 m. The glacier snout advanced 263 more pronouncedly at 4.9 m d⁻¹ between 18 December 2018 and 8 May 2019, however, this 264 265 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-266 267 March, March-April and April-May, May-September respectively.

268

269 **4.4. Evolution of the ice-dammed lake**

270 The snout advance of Shisper Glacier blocked the water stream originating from the adjacent 271 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 272 273 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 274 275 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. 276 277 The lake completely emptied by July 2019 (**Figure 8i**)

278 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 m³, 6.14 million m³ and 5.03 million m³ 279 respectively. The corresponding peak discharges as per equation (5) are 5680.06 m³s⁻¹, 280 6167.41 m³s⁻¹ and 5033.04 m³s⁻¹ from the current ice-dammed lake. If it were to drain 281 rapidly, this could pose flood risk to the population living in Hassanabad hamlet and adjacent 282 283 areas. However, the lake drained quite steadily starting on 22 June 2019, damaging a part of 284 Karakoram highway and adjacent river banks while Shisper Glacier continued to be in a state 285 of surge.

286

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**). 295 The areas, 157 buildings, falling within the 5 delineated cross-sections that could be 296 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 297 298 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 299 300 precisely quantify the area at risk. Since the glacier is currently in an active state of surge we 301 predict the formation of the ice-dammed lake again during the onset of winters owing to the 302 freezing temperatures that may freeze the glacier bed. The water may get siphoned off again 303 during the onset of summer later next year but the rate of release will depend on whether the 304 glacier remains in the surge phase or not. Similar phenomena have been observed in 305 surrounding glaciers in the region, the recent one being Kyagar glacier surge and formation 306 of an ice-dammed lake (Veh et al., 2019).

307

308 **5.** Discussion

309 The reports pertaining to the surge of Shisper glacier date back to late nineteenth century 310 (Hayden, 1907). Literature suggests that Shisper glacier and its adjoining Mochowar glacier 311 were tributaries of a single erstwhile glacier-Hassanabad. Due to a 7 km retreat, the 312 Hassanabad glacier fragmented into two glaciers-Shisper and Mochowar in 1954 (Paffen et 313 al. 1956). The glaciers joined together in 1972 owing to the surge of Mochowar glacier 314 (Bhambri et al. 2017). Shisper glacier surged again from 1972-1976 and 1993-2002 (Bhambri 315 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 316 317 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 318 319 the recurrence interval of surges of individual glaciers.

320 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 321 322 glacier, however, due to the onset of winter the glacier velocity decelerated appreciably. The 323 rise in the surface velocities again between February--May 2019 could be possibly attributed 324 to rise in temperatures from winter to spring that might have accelerated the melt processes 325 (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 326 327 been reported for surging Hispar (Paul et al., 2017), Khurdopin (Steiner et al., 2018) and 328 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 m³s⁻¹. This data together with valley cross-section profiles 345 suggested that the rapid drainage of the ice-dammed lake could pose a huge risk to the 346 347 population (>650 people) and associated infrastructure (>150 buildings) downstream. It is 348 worth remembering that the outburst flood of Chorabari Taal in Kedarnath that resulted in a peak discharge of 783 m³ s⁻¹ (Rao et al., 2014), seven times lower magnitude compared with 349 350 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, 351 352 2013). The lake however drained quietly later half of June without substantial damage 353 although studies indicate that such ice-dammed lakes can result into destructive outburst 354 floods (Hewitt and Liu, 2010). This indicates that empirical approaches of quantifying peak 355 discharge of ice-dammed lakes resulting due to surging glaciers are not appropriate to 356 quantify risk of such lakes to downstream population.

357

358 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 m³ and 373 6.14 million m³ with peak discharge potential of 5626 m³s⁻¹ and posing a potential 374 375 flood risk to downstream population and infrastructure. However, the lake waters released steadily during June 2019 damaging a small portion of the Karakoram 376 highway without damaging any infrastructure. This indicates that empirical 377 378 approaches of quantifying peak discharge are not appropriate to quantify risk to 379 population living downstream. There is, however, a likelihood that the currently 380 active surging Shisper glacier may again result into the formation of an ice-dammed 381 lake as winters arrive in the region.

382

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388

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609 **Figure Captions:**

- Figure 1. Location of the study area. Background: Landsat 8 OLI True Colour Composite
 image acquired on 10th July 2018.
- 612 **Figure 2.** Mean and maximum velocity (m d⁻¹) of Shisper glacier between March 2018 and
- 613 May 2019. Red indicates 2018 while purple indicates 2019.
- 614 **Figure 3.** Glacier-wide surface velocity of Shisper between March 2018 and May 2019: (a)
- 615 March-April 2018; (b) April-June, 2018; (c)June-July 2018; (d) July-August, 2018; (e)
- 616 August-September 2018; (f) September-October, 2018; (g) October-November 2018; (h)
- 617 November-December 2018; (i) December 2018-January 2019; (j) January-February 2019; (k)
- 618 February-March 2019 and (l) March-May 2019.
- 619 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.
- 621 Figure 5. Supraglacier moraine dynamics: (a) March 2018; (b) April 2018; (c) June 2018; (d)
- 622 July 2018; (e) August, 2018; (f) September 2018; (g) October 2018; (h) February 2019 and (i)
- 623 April 2019.
- 624 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)
- 626 Purple-June, Cyan-July 2018; (d) Cyan-July, Red-August 2018; (e) Red-August, Yellow-
- 627 September, Cyan-October, Green-November, and Orange-December 2018; (f) January 2019;
- 628 (g) March 2019; (h) April 2019; (i) May 2019; (j) June 2019; (k) July 2019 and (l) Cyan-
- 629 August, Purple-September 2019. Arrows indicate position of snout at the time of surge:
- 630 Cyan-February 2018 and Red: Current snout position (September 2019).
- Figure 7. Snout advance of Shisper Glacier February 2018 and September 2019. Redindicates 2018 while purple indicates 2019.
- 633 Figure 8. Ice-dammed lake expansion between November 2018 and July 2019: (a)
- 634 November, 2018; (b) December 2018; (c) January 2019; (d) February 2019; (e) March 2019;
- 635 (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 satellitedata.
- 638 Figure 10. Valley cross-section profiles for determining the potential to withhold outburst
- 639 flood waters (a) CS1; (b) CS2; (c) CS3; (d) CS4 and (e) CS5.
- 640 **Figure 11.** Settlements potentially facing outburst flood risk.