Glacial and geomorphic effects of a supraglacial lake drainage and outburst event, Everest region, Nepal Himalaya

Evan S. Miles, C. Scott Watson, Fanny Brun, Etienne Berthier, Michel Esteves, Duncan J. Quincey, Katie E. Miles, Bryn Hubbard, and Patrick Wagnon

Final Response

12/11/2018

Dear Professor Farinotti,

We have received two reviews to our manuscript, both of which were extremely supportive of our analysis and interpretations, and we have adapted the manuscript in light of their constructive comments. In the document below, the reviewers' comments appear in italicized blue, followed by our response from the open discussion in normal black text, and in red font we have indicated the changes made to the updated manuscript. Along with this letter, we are submitting the revised version of the manuscript and a version with changes marked.

In addition, we have made very minor textual changes for clarity and adjusted the precision of values in Table 1 to better reflect our confidence in the measurements.

There are a two minor changes to the manuscript that were not directly stimulated by the reviewers, and which I would like to note. First, based on internal discussions during the review process, we decided to revise the title to 'Glacial and geomorphic…' as the changes at the glacier surfaces are not necessarily strictly indicative of ablation. Second, and also after internal discussion during the review process, we have decided to include Bryn Hubbard as a co-author. This is due to his support of our field investigations, and to acknowledge extensive discussions between the authors and Bryn related to the drainage pathways of these glaciers, particularly in the situation of an outburst flood. Those discussions led, for example, to the development of a third hypothesis for the double-peak flood hydrograph, which is now included in the text.

Thank you for your consideration of our revised manuscript, which we hope is now acceptable for publication. Please address correspondence to me at evan.miles@wsl.ch

Sincerely,

Evan Miles and Co-authors

Comments by Reviewer #1, Doug Benn, and responses:

This is an excellent paper, which provides very rare detailed documentation of a transient drainage event from a Himalayan glacier. It is exceptionally well written, and presents the methods and results in a clear and logical way. The interpretations and conclusions are sound and convincing. I can find no fault with the paper, and have only a few remarks, mostly relating to pertinent unpublished observations.

Dear Doug,

Thank you very much for your supportive review. We are very happy that you enjoyed the paper, and are of course delighted to hear of the independent evidence supporting our interpretations regarding the flood's flowpath. We respond to your specific comments individually below, with your comments appearing in italics and our response in normal text.

Kind regards,

Evan and Co-authors

p. 2, line 20: nature of the flow path into Khumbu Glacier. In 2006, Jason Gulley and I entered an ice cave in the margin of Khumbu Glacier at the bottom of the Changri proglacial gorge. The entrance led into a low, wide passage that trended along parallel to the slope. The passage was floored by boulders resting on bedrock, so any water entering the glacier would flow along the ice-bed interface, at least initially. This was also one of the most dangerous places we had ever been, owing to rocks occasionally bouncing down the gorge, so we did not linger long enough to make any surveys.

Perhaps the fact that the system was subglacial in 2006 could be added as a 'pers. comm.'

This observation also helps to support the authors' interpretation of the flood flowpath through Khumbu Glacier, presented on p. 9, line 15. Interestingly, there is also evidence of a sub-marginal / englacial drainage system on Ngozumpa Glacier, which is intermittently connected to the supraglacial / englacial system. The same may be true on Khumbu Glacier - although the flood likely bypassed the supraglacial - englacial system inferred by Irvine-Fynn et al. (2017), the two systems may not be entirely and perennially separate.

P2, L20: The unpublished observations from 2006 are very interesting indeed, and we will include a citation to these observations as suggested. Several of the authors have passed through the gorge to reach Gorak Shep from the glacier surface, but did not venture into the cave and inlet. We heartily agree that this is a very dangerous area, especially during the melt season. Nonetheless the observation of the passage's floor characterized by boulders resting on bedrock is extremely valuable to confirm our interpretation of a subglacial flowpath from this point (at least initially). Thank you for sharing your observations.

Text modified to read: "The stream has cut into the lateral margin of Khumbu Glacier, leading to development of a large bare ice cliff. From this position, water initially flows into a low, wide passage along the ice-bed interface (D. Benn, pers. comm., 23 August 2018)."

It is interesting as well to speculate whether this flowpath simply connects to a sub-marginal drainage system from up-glacier, or whether it is the sole cause for this particular flowpath. Our discussions of the structure of the Khumbu drainage system are still ongoing, but in May 2017 we were able to trace a surface channel to just up-glacier of the Changri gorge. It is still unclear whether these flowpaths (the surface/near-surface from the glacier's upper debris area and the lateral input from Changri) connect directly or closer to the terminus, or the nature of their connection with the supraglacial-englacial system.

As you suggest, the systems may not be entirely and perennially separate, and we may have presented the 'bypass' too simply. One very possible scenario is that the flood's passage through Khumbu Glacier overpressured the subglacial system, leading to the partial emergence of the flood at the surface flowing through the linked ponds and contributing to the double (or triple) peak in the hydrograph. We will discuss this possibility briefly in the revised manuscript, but what is very clear is that the flood exploited a subglacial flowpath for part of its transit through Khumbu Glacier.

Discussion of the multiple peaks now reads: "The double peak of discharge observed at Pheriche (Figure 7) is unusual for outburst floods. A possible cause is the blockage of the Khumbu stream inlet by the landslide in the Changri Shar proglacial gorge (Figure 4). This is likely to have initiated around peak flow through the gorge, and could have led to a substantial decline in discharge, followed by a later, sudden increase as preferential flowpaths developed through the debris (Gulley et al., 2009b). A second explanation is the possibility of multiple flowpaths for the flood through the lower part of Khumbu Glacier. As Khumbu Glacier exhibits a low terminus slope and high hydraulic base level, the flood may have temporarily overwhelmed the subsurface drainage network and, exploiting fractures and secondary pathways common for these glaciers, partially emerged at the glacier surface. This would result in two or more flowpaths of differing efficiency, possibly leading to distinct discharge peaks on the Pheriche hydrograph. This possibility is supported by the appearance of highly turbid water in the ponds between zones E-G (Figure 2) during drainage. A third possibility is that the increased discharge late on 16 July corresponds to delivery of water stored elsewhere within the glacier system. Such stored water might connect to the drainage system more efficiently by the opening of conduits and channels during the flood. Regardless, 5 it is clear that the increase in discharge at Pheriche only lasts until 10:00 on 17 July, so the flood's direct contribution to discharge was short-lived."

p. 7, line 7: hydrofracture is unlikely because the lower Changri glacier is stagnant - see Benn et al. 2009 for a discussion of the conditions required for hydrofracture on Khumbu Glacier.

P7, L7: True, we will adjust this text in the revision.

Modified text reads: "Based on the lack of down-glacier surface change on Changri Shar, the lake must have drained englacially or subglacially, rather than along the surface. Hydrofracture is an unlikely scenario as the ice is nearly stagnant in this area; rather, this could have been accomplished by penetrating the internal blockage or establishing a new connection to relict conduits."

Comments by Reviewer #2, Dave Rounce, and responses:

This study uses a series of high-resolution satellite images to document the filling and coalescing of supraglacial ponds on Changri Shar Glacier that rapidly drained in July 2017 causing a glacier outburst flood. High-resolution DEMs were used to analyze the geomorphic changes caused by the outburst flood, and the social impacts were considered as well. The study was very well written and easy to follow. Figures, albeit a little small at times, contained significant amounts of information that supported the text well. The study's use of highresolution satellite imagery combined with multiple DEMs enabled a very novel approach for quantifying the flood volume. The flow measurements and field observations also provided unique insight into the timing and path of the flood, and supported the interpretation of events. The discussion contextualized the study well, highlighting (i) the power of being able to use a suite of remote sensing products to observe and quantify glacier outburst floods, and (ii) the impacts that these glacier outburst floods can have on local communities. Given the lack of observations of glacier outburst floods, the holistic nature and level of detail in which this event was analyzed, and how well written this study was, I recommend this manuscript be accepted. A few minor comments may be found below.

Dear Dave,

Thank you for your careful and positive review. Thank you also for the comments and questions, which will improve the manuscript's clarity. We will certainly reconsider the figure size (and especially the font size within the figures) to improve their readability for the revised manuscript. We respond to your specific comments individually below, with your comments appearing in blue italics and our response in normal text.

Kind regards,

Evan and Co-authors

Figure 1 – There is a lot of information in this figure, but I found key aspects of the figure a bit difficult to read. For example, this figure introduces readers to the general area, so the names of the glaciers should be clear (they are very small and hard to read). After looking at the figure for a while, the inset figure clearly shows the maximum area, but the legend does not state this nor is this mentioned in the caption. I would simply make note of this in the caption, so the reviewer knows they are looking at how the maximum lake extent fills and drains. If possible make the text larger.

Thank you for the suggestions. We will certainly increase the font size in this figure (and others) for key aspects, and will include a reference in the caption to the display of maximum lake area in the inset figures.

We have reexamined the font sizes for all labels in the figure and have made numerous adjustments to improve the clarity of the figure.

P3 L23-28 – Does this mean you avoided all areas that had a supraglacial pond or ice cliff in the previous year? Please add a sentence here detailing how you identified areas where surface lowering was not attributable to cliffs and ponds, since it is not very clear.

Regarding this section, we agree that this text was slightly ambiguous, and should be clarified. The current text reads 'not solely attributable to ice cliffs and supraglacial ponds' and later mentions 'clearly associated with the lake drainage.' By this we do not mean that cliffs and ponds were entirely excluded or played no role, but that we could not explain the zone of surface lowering only by the presence of cliffs and ponds. Our rationale appears below, but we will carefully modify the text to succinctly describe that we have avoided pond water-level lowering and areas that had a thin, arcuate form, but focused specifically on broad areas of enhanced elevation change with initial changes visible in the Planet imagery.

The delineation process for zones of enhanced change focused on identifying zones of considerable elevation change with three key characteristics:

1) We first ensured that zones of elevation change were not attributable to pond water level change. This is straightforward to avoid as such zones would have been ponds in the March Pleiades image.
2) We aimed to identify zones inexplicable by ice cliff backwasting. Backwasting rates for Khumbu Glacier are 1-6 cm d^{-1} (Watson et al, 2017), depending on season and local characteristics. Over the period between our two Pleiades DEMs (266 days between 23 March and 14 December 2017), this would total 2.7-16.0 m of cliff retreat. This linear change could be adjusted by the cliff's advection down-glacier (e.g. Brun et al, 2018), but Khumbu is nearly stagnant below the Changri inlet, so we neglect this.
   As cliffs tend to have arcuate or linear forms several 10s of meters in length, but backwaste up to ~10 m during the melt season, the features leave a characteristic thin arc of enhanced mass loss in our dH data, which is due to the high spatial resolution of the DEM and the relatively short interval between acquisitions. We ignored these forms (clearly visible in Figure 2) entirely, but focused on broad (i.e. >40 m across), continuous areas of elevation change.
3) The third necessary characteristic is that minimal change was evident in the Planet imagery prior to the lake drainage.

Although this process was subjective, we were as conservative as possible. For example, field evidence suggested that many of the changes in the area shown in Figure 5e (location shown in 5a) were probably due to the passage of the flood, but the pattern of dH in this area appears similar to ice cliff backwasting, so we did not include it in our analysis. Without a doubt, it is not possible to entirely separate the effects of cliff and flood: the passage of water directly leads to exposure of steep, bare ice (i.e. a cliff).

Revised text now reads "This geodetic difference encompassed the majority of the ablation season, so for the glaciers we focused on zones of enhanced surface lowering not solely attributable to ice cliffs and supraglacial ponds, which are known hot spots of melt for Himalayan debris covered glaciers (e.g. Sakai et al., 2002). Ice cliffs tend to have curvilinear forms, with their planimetric length much greater than their width (e.g. Brun et al., 2016; Kraaijenbrink et al., 2016). For our study area, we are able to neglect advection and emergence of these features due to glacier dynamics (e.g. Brun et al., 2018), as the lowest 5 km of Khumbu Glacier is stagnant (Rounce et al., 2018). Over a short interval, melt along the inclined cliff surface was thus expressed as a thin arc of surface lowering (e.g. Immerzeel et al., 2014), clearly identifiable in Figure 2.We ignored these cliff areas and areas of elevation change within ponds. We thus identified 11 zones of prominent elevation change that were clearly associated with the lake drainage according to the PlanetScope and RapidEye imagery (Table 1, Figure 2). Field visits in May 2017, October 2017, and May 2018 enabled direct observation of many of the most prominent zones of change."

P4 L9 – "by a cloud" or "by clouds"?

True, "by clouds." We will adjust this in the revised manuscript.

Adjusted.

P5 L16 vs. L17 & L32 – I think it is better to be explicit when referring to the zones like L16 "Zone A in Figure 2"; however, on L17 and 32, the zones are just stated. I suggest being consistent throughout the text in how you refer to them. Either always refer to them as Zone _ in Figure 2, or change L16.

Thank you for the suggestion. We had decided to refer the reader to the pertinent table and figure at the first instance only, but we agree that it is probably easier for the reader if we refer them at each instance.

Adjusted.

P7 L9 – This appears to reference Figure 4c, not 3c.

Thank you! We will adjust this in the revised manuscript.

Corrected.

P7 L24 – This appears to reference Rounce et al. (2017) not Rounce et al. (2016).

You are correct, our apologies! This will be corrected in the revised manuscript.

Corrected.

P7 L26-28 – I found this sentence unclear and difficult to read. What do you mean by "of this area in similar conditions"? Also, "examining available historic satellite image archives we have not found" does not make sense – perhaps split this into two sentences: "The area of bank erosion is greatly magnified during 2016-17. This magnitude of geomorphic change appears to be uncommon, since we were unable to find similar areas of bank erosion in any of the historic satellite image archives"?

Thank you for the suggestion, which we will implement in the revised manuscript.

The text now reads: "The 2016-2017 NDWI and NDVI changes show a greater magnitude of channel migration despite the shorter interval. The area of bank erosion is also greatly enhanced during 2016-2017. The magnitude of geomorphic change associated with the flood appears to be uncommon, since we were unable to find similar areas of bank erosion in any of the historic satellite image archives."

P7 L29 – It appears that at least a portion of the second peak is simply due to the diurnal signal caused by the melting of the glacier. On July 14th, the flow increased by approximately 3 m3 s -1 , compared to this second peak where it increases around 3.5 – 4 m3 s -1 ; hence, it doesn't seem unreasonable that this is simply the extra discharge coming from the glacier melt. It's timing is consistent as well. This seems much more likely than a possible blockage, since one would expect that the flood would generate very efficient channels, which would make something getting blocked unlikely.

We certainly agree that some of the second peak is simply due to the diurnal signal, and have estimated that portion based on the diurnal discharge patterns preceding and following the event (the black line in Figure 7). The second peak corresponds to an increase of 6.5 $m^3 s^{-1}$ (see P6 L14-18; note that Figure 7 has a logarithmic scale), which is greater than the diurnal variation preceding the event.

The blockage hypothesis corresponds to the landslide in the Changri gorge, which definitely occurred on the 16th. This deposit of mass would have choked the entrance to the sub-marginal drainage path, preventing access to the englacial and subglacial channels altogether, but the debris blockage would be unlikely to prevent drainage for long, and would thus be a potential candidate for one of the peaks later on the 16th.

A third possible explanation, that of multiple flowpaths, has arisen from internal discussions since the manuscript submission, and we will also adapt the manuscript to briefly include it in the discussion. We think it likely that the flood's passage through Khumbu Glacier would have temporarily overpressured the subglacial system. In this case, water would try to exploit weaknesses in the ice to drain to the surface. We see evidence for surface routing of at least part of the flood from the zones of enhanced elevation change (e.g. Figure 5) and from increased turbidity of the chain of terminal ponds on the 16th and 17th of July. However, this does not mean that the entire flood would have been routed to the surface; instead, only the water which could not be accommodated by subglacial and englacial conduits would find its way to the surface. As the surface flowpath is inefficient (Irvine-Fynn et al, 2017), this would lead to at least two distinct traces at the Pheriche station.

We will be sure to represent all three potential hypotheses in the revised manuscript.

The revised text now reads: "The double peak of discharge observed at Pheriche (Figure 7) is unusual for outburst floods. A possible cause is the blockage of the Khumbu stream inlet by the landslide in the Changri Shar proglacial gorge (Figure 4). This is likely to have initiated around peak flow through the gorge, and could have led to a substantial decline in discharge, followed by a later, sudden increase as preferential flowpaths developed through the debris (Gulley et al., 2009b). A second explanation is the possibility of multiple flowpaths for the flood through the lower part of Khumbu Glacier. As Khumbu Glacier exhibits a low terminus slope and high hydraulic base level, the flood may have temporarily overwhelmed the subsurface drainage network and, exploiting fractures and secondary pathways common for these glaciers, partially emerged at the glacier surface. This would result in two or more flowpaths of differing efficiency, possibly leading to distinct discharge peaks on the Pheriche hydrograph. This possibility is supported by the appearance of highly turbid water in the ponds between zones E-G (Figure 2) during drainage. A third possibility is that the increased discharge late on 16 July corresponds to delivery of water stored elsewhere within the glacier system. Such stored water might connect to the drainage system more efficiently by the opening of conduits and channels during the flood. Regardless, 5 it is clear that the increase in discharge at Pheriche only lasts until 10:00 on 17 July, so the flood's direct contribution to discharge was short-lived."

P8 L25 – The use of "low" here is a bit awkward. Consider "melt-inhibiting thick debris near the terminus on such glaciers" or something similar.

Agreed, thank you.

Adjusted.

P9 L2 – “region” not “regional”

Agreed, thank you.

Adjusted.

References in the response

Brun, F., Wagnon, P., Berthier, E., Shea, J. M., Immerzeel, W. W., Kraaijenbrink, P. D. A., Vincent, C., Reverchon, C., Shresta, D., and Arnaud, Y. (in review, 2018). Can ice-cliffs explain the debris-cover anomaly? New insights from Changri Nup Glacier, Nepal, Central Himalaya, *The Cryosphere Discuss.,* https://doi.org/10.5194/tc-2018-38.

Watson, C. S., Quincey, D. J., Smith, M. W., Carrivick, J. L., Rowan, A. V., & James, M. R. (2017). Quantifying ice cliff evolution with multi-temporal point clouds on the debris-covered Khumbu Glacier, Nepal. *Journal of Glaciology*, *63*(241), 823–837. https://doi.org/10.1017/jog.2017.47

~~Ablative~~ Glacial and geomorphic effects of a supraglacial lake drainage and outburst event, Everest region, Nepal Himalaya

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Abstract. A set of supraglacial ponds ~~rapidly filled~~ filled rapidly between April and July 2017 on Changri Shar Glacier in the Everest region of Nepal, coalescing into a ~180,000 m^2 lake before sudden and complete drainage through Changri Shar and Khumbu ~~Glaciers~~ glaciers (15-17 July). We use ~~a suite of~~ PlanetScope and Pléiades satellite orthoimagery to document the system's evolution over its very short filling period and to assess the glacial and proglacial effects of the outburst flood. We ~~additionally use high resolution~~ also use high-resolution stereo digital elevation models (DEMs) to complete a detailed analysis of the event's ~~ablative~~ glacial and geomorphic effects. Finally, ~~measurement of the flood's passage~~ we use discharge records at a stream gauge 4 km downstream ~~enables a refined~~ to refine our interpretation of the chronology and ~~overall~~ magnitude of the outburst. We infer largely subsurface drainage through both of the glaciers located on its flowpath, and efficent drainage through the lower portion of Khumbu Glacier. The drainage and subsequent outburst of ~~$1.36 \pm 0.19 \times 10^6$~~ $1.36 \pm 0.19 \times 10^6$ m^3 of impounded water had a clear geomorphic impact on glacial and proglacial topography~~at least as far as 11 km downstream~~, including deep incision and landsliding along the Changri Nup proglacial stream, the collapse of shallow englacial conduits near the Khumbu terminus and extensive, enhanced bank erosion at least as far as 11 km downstream below Khumbu Glacier. These sudden changes ~~led to the rerouting of~~ destroyed major trails in three locations, demonstrating the potential hazard that short-lived, relatively small glacial lakes pose.

1 Introduction

Outburst floods occur due to the sudden release of ~~stored~~ water from glaciers~~, which~~. This water can be stored within topographic lows at the glacier surface ~~within topographic lows~~ (Benn et al., 2012; Chu, 2014); internally along englacial conduits, crevasses, and voids (Fountain and Walder, 1998); ~~and~~ or at the glacier's bed (Jansson et al., 2003). Water can also be impounded by the glacier or its moraines to form ice-marginal or proglacial lakes~~; outburst~~. Outburst floods from such lakes can lead to catastrophic geomorphic change and subsequent societal impacts reaching far downstream, and have been a topic of focused study in High Mountain Asia (e.g. Benn et al., 2012; Westoby et al., 2014; Rounce et al., 2016; Narama et al., 2018;

Nie et al., 2018; Veh et al., 2018) and globally (e.g. Carrivick and Tweed, 2016; Cook et al., 2016; Harrison et al., 2018). Outburst floods from water ~~stored~~ within the glacier system are generally smaller in magnitude, but they can occur repeatedly due to seasonal and interannual variations in storage within a glacier's hydrological system, whether ~~impounded supraglacially and englacially (e.g. Benn et al., 2017; Miles et al., 2017a; Rounce et al., 2017; Narama et al., 2017; Watson et al., 2017) or~~ water is impounded supraglacially (Miles et al., 2017a; Narama et al., 2017; Watson et al., 2017), englacially (e.g. Benn et al., 2017; Rounce et a , subglacially (e.g. Walder and Driedger, 1995; Wadham et al., 2001; Garambois et al., 2016), or ~~due to ice-marginal dynamics~~ adjacent to ice margins (Huss et al., 2007; Steiner et al., 2018). These storage components are interlinked: water retained at the surface can reach englacial and subglacial systems through hydrofracture or exploitation of zones of permeability (e.g. Gulley et al., 2009b), while water impounded within or beneath the glacier can drain surficially if subglacial water pressures rise ~~substantially (e.g. Roberts et al., 2002).~~ sufficiently (e.g. Roberts et al., 2002). All of these can also drain into ice-marginal water bodies.

Despite their smaller magnitude, glacier outburst floods that emanate from supraglacial and englacial sources can be severely damaging to infrastructure, yet they have not received focused study in the Himalaya (Richardson and Quincey, 2009; Rounce et al., 2017). The low density of hydrologic gauging stations limits hydrograph observation, while aerial and satellite observation of supraglacial water storage is hampered by the South Asian Monsoon, obscuring the glacier surfaces with clouds when supraglacial ponding is most prevalent (Watson et al., 2016; Miles et al., 2017a). Nonetheless, recent observations have indicated that these smaller floods can occur with regularity and have the potential to be hazardous (Rounce et al., 2017; Narama et al., 2018).

Changri Shar Glacier is a valley glacier in the Everest region of Nepal (Figure 1). The glacier is characterised by a 4.0 km^2 debris-covered tongue extending from an elevation of ~5500 m a.s.l to ~~the~~ its terminus at ~5070 m a.s.l. The thick surface debris of the glacier tongue greatly retards surface ablation and leads to hummocky surface topography. Changri Shar and the neighbouring Changri Nup Glacier (Vincent et al., 2016; SHERPA et al., 2017) discharge water into a proglacial gorge, which funnels water into the true-right side of Khumbu Glacier~~, for which the glaciers constituted a former tributary~~. The stream has cut into the lateral margin of Khumbu Glacier, leading to development of a large bare ice cliff~~, and this water flows englacially or subglacially to join the Khumbu drainage system.~~ . From this position, water initially flows into a low, wide passage along the ice-bed interface (D. Benn, pers. comm., 23 August 2018). Changri Shar, Khumbu, and other debris-covered glaciers in the area are generally responding to local climate warming through surface lowering and stagnation, rather than ~~retreat~~ recession (e.g. Rowan et al., 2015; King et al., 2017). These factors combine to create very low surface gradients for the lower ablation area, and increase the likelihood of formation of large proglacial or supraglacial lakes in this zone (Quincey et al., 2007; Miles et al., 2017a; King et al., 2018).

In the pre-monsoon period of 2017, a large supraglacial lake developed over a period of three months on the Changri Shar Glacier, and drained suddenly within a short window in the monsoon. Here, we combine PlanetScope, RapidEye, and Pléiades optical satellite imagery ~~along~~ with field observations and a discharge record to document the expansion and drainage of this supraglacial lake system, and to describe its ~~ablative and geomorphic impacts on the~~ impacts on Khumbu Glacier, through which the flood travelled. Finally, we highlight the impact of the flood on the downstream river system by quantifying rates of bank erosion and channel migration.

2 Methods

2.1 Supraglacial lake area

To document the supraglacial lake expansion, we analysed 25 Level 3B tiles collected by the PlanetScope Dove satellite constellation between 27 March 2017 and 26 October 2017 (Table S1). These 4-band data have a ground sampling distance of 3.7 m but are resampled to 3 m during orthorectification, and digital numbers (DNs) contain scaled at-sensor radiance values for the Blue (B: 455-515 nm), Green (G: 500-590 nm), Red (R: 590-670 nm), and Near-Infrared (NIR: 780-860 nm) spectral ranges. We ~~additionally~~ also used several RapidEye level 3B tiles for pond coverages and geomorphic interpretations. These are 5-band data (B: 440-510 nm; G: 520-590 nm; R: 630-685 nm; Red Edge: 690-730 nm; NIR: 760-850 nm) with a ground sampling distance of 6.5 m, resampled to 5 m during orthorectification (Planet Team, 2017). Due to the high density of clouds during the monsoon, few scenes are cloud-free over the full study area~~; we therefore manually~~ . We therefore masked clouds and cloud shadows manually in the region of the supraglacial lake before mapping ponded water (~~inset panels, Figure 1~~ Figure 1 panels b-i). For each scene, we calculated the Normalised Difference Water Index (NDWI) based on DNs for the G and NIR bands (NDWI $= \frac{G-NIR}{G+NIR}$; e.g. McFeeters, 1996) and used an Otsu adaptive histogram-based approach to select an optimised NDWI threshold (Otsu, 1979; Cooley et al., 2017), identifying ponded water as those pixels exceeding this threshold. Finally, the pond cover products were again ~~manually inspected for removal of~~ inspected manually to remove terrain and cloud shadows before ~~development of a lake areatime series~~determination of multi-temporal lake area, and we ~~use~~ used a $\pm$1-pixel buffer for lake area uncertainty (e.g. Gardelle et al., 2011).

2.2 DEM generation and surface elevation changes

We ~~then~~ analysed two along-track Pléiades triplets (Berthier et al., 2014) with acquisition dates of 23 March 2017 and 14 December 2017, bounding the lake's filling and drainage. The two scenes had maximum base-to-height ratios of 0.55 and 0.32, respectively. Their panchromatic bands (480–830 nm, ground sampling distance of 0.7 m) were processed using the Ames Stereo Pipeline (Shean et al., 2016) to generate DEMs and orthoimages at 2 and 0.5 m resolution, respectively. The two Pléiades DEMs were 3D-coregistered using off-glacier terrain (Berthier et al., 2007), then differenced to produce a map of surface elevation change (dH) spanning the 2017 monsoon period.

This geodetic difference encompassed the majority of the ablation season, so for the glaciers we focused on zones of ~~heightened~~ enhanced surface lowering not solely attributable to ice cliffs and supraglacial ponds, which are known hot spots of melt for Himalayan debris covered glaciers ~~(Immerzeel et al., 2014; Thompson et al., 2016; Ragettli et al., 2016). We~~ (e.g. Sakai et al., 200
. Ice cliffs tend to have curvilinear forms, with their planimetric length much greater than their width (e.g. Brun et al., 2016; Kraaijenbrink et
. For our study area, we are able to neglect advection and emergence of these features due to glacier dynamics (e.g. Brun et al., 2018)

, as the lowest 5 km of Khumbu Glacier is stagnant (Rounce et al., 2018). Over a short interval, melt along the inclined cliff surface was thus expressed as a thin arc of surface lowering (e.g. Immerzeel et al., 2014), clearly identifiable in Figure 2. We ignored these cliff areas and areas of elevation change within ponds. We thus identified 11 zones of prominent elevation change that were clearly associated with the lake drainage according to the PlanetScope and RapidEye imagery ~~to interpret the ablative and geomorphic effects of the supraglacial lake drainage~~ (Table 1, Figure 2). Field visits in May 2017, October 2017, and May 2018 enabled direct observation of many of the most prominent zones of change.

To assess the error on the elevation difference obtained by differencing of two Pléiades DEMs, we follow the tile ~~methods~~ method of Berthier et al. (2016) and split the stable terrain dH maps into $n \times n$ tiles, with n varying from 2 to 200. The corresponding individual tile area thus varies from 91.2 km^2 ($n = 2$) to ~~0.04~~ 0.01 km^2 ($n = 200$). For each tile, we compute the absolute value of the median dH. We then calculate our dH error (σ_{dH}) as the average of these n^2 absolute values, and σ_{dH} ranges from 0.12 m ($n = 2$) to 0.64 m ($n = 200$). In ~~the Figure 2inset~~Figure 2b, dH is plotted as a function of the individual tile area. The relationship is well represented by a logarithmic fit which we use as our error model. Consequently, for all our zones of change we estimate an error based on the zone area, and only analyse elevation changes of magnitude greater than this error.

2.3 Lake volume estimation

Using the ~~pond-free~~ pre-lake March 2017 Pléiades DEM, we identified 142 closed surface depressions and determined ~~area-volume~~ depth-area-volume relationships for each by progressively filling ~~the surface depressions~~ them with an increment of 0.1 m depth ~~(as in, e.g. Watson et al., 2017)~~(following e.g. Watson et al., 2017). We then calculated stored water volumes in the supraglacial lake area for each PlanetScope scene by estimating the volume of each individual pond in the area of the supraglacial lake, then summed these to estimate the total ponded volume in the study area (Figure 3). On 16 July the lake was partially obscured by ~~cloud, so~~ clouds, so for this scene we instead estimated the water level and volume from a partial shoreline dataset (Figures S1 and S2). This approach assumes ~~very minor~~ negligible topographic changes in the proximity of the supraglacial lake during the study period, but many studies have noted the local ~~ablative effects of supraglacial ponds (Benn et al., 2001; Röhl, 2008; Brun et al., 2016; Miles et al., 2016; Salerno et al., 2017)~~ablation associated with supraglacial ponds (Benn et al., 2001; Röhl, 2008; Miles et al., 2016; Salerno et al., 2017). Thus, the resulting volume estimates carry considerable uncertainty (in this case calculated using the $\pm$1-pixel areal uncertainties), but are nonetheless useful ~~and conservative~~ in providing minimum values of supraglacial water storage during this period.

2.4 Proglacial bank erosion and channel migration

We also measured areal changes associated with active channel migration and bank erosion along the Khumbu proglacial stream as far as Pheriche using RapidEye level 3B imagery from November of 2012, 2015, 2016, and 2017. The images were coregistered in ENVI (RMSE < 1 m), then we calculated changes in the NDWI and Normalised Difference Vegetation Index (NDVI $= \frac{NIR-R}{NIR+R}$) for 2012-2015 and 2016-2017, enabling us to resolve periods preceding and ~~encompassing~~ spanning the 2017 ~~outburst from Changri Shar .~~ Changri Shar outburst. Outburst floods from Imja Khola during 2015 and

2016 (Rounce et al., 2017) may have affected bank erosion and channel migration change over the period of analysis, but this tributary joins the Khumbu proglacial stream below Pheriche.

We considered the major NDVI changes (all decreases) to indicate bank erosion and reactivation, while ~~strong NDWI changes indicate~~ marked spatial changes in NDWI indicated stream migration. We calculated a 3x3 focal mean to reduce noise, then eliminated low-magnitude changes in the indices based on a visual inspection of the histogram (thresholds in Table 2). We manually trimmed the results to zones within the channel, also eliminating areas severely affected by shadows. Finally, we aggregated areas of bank erosion and stream migration in 1 km bins along the main Khumbu ~~Khola~~ River to compare rates of change preceding and bounding the event (Table 2).

2.5 ~~Discharge measurements at Pheriche~~Proglacial discharge

~~Finally, the~~ The study period coincided with automated water level measurements collected every 30 minutes in the proglacial stream near Pheriche village (Figure 1). A rating curve has been developed for this position based on 34 field-calibrated fluorescein discharge measurements collected since November 2010 and was used to calculate discharge for the period of analysis. Based on the analyses of Di Baldassarre and Montanari (2009) and Mcmillan et al. (2012), we estimated a discharge uncertainty of 15% for stage values within the calibrated range and 20% for stage values above the maximum stage-discharge measurement. From this record, we estimate ~~normal~~ background discharge (hereafter, baseflow) ~~for~~ from 17:00 on 15 July to 09:00 on 17 July (all times given in Nepal Time, NPT; UTC +05:45) using a half-hourly cubic spline interpolant fitted to measurements for 10-15 and 17-20 July (i.e. interpolating between preceding and subsequent 09:30 measurements to estimate discharge at 09:30 on 16 July), and determine the flood discharge as the difference between observed discharge and estimated baseflow.

3 Results

Prior to 2017, the area of the Changri Shar supraglacial lake was characterised by occasional ponds filling and draining, both seasonally and interannually. Surface depressions in the study area began to accumulate water in March 2017 (Figure 3), likely due to the seasonal blockage of shallow subsurface englacial pathways (Benn et al., 2017; Irvine-Fynn et al., 2017; Miles et al., 2017b). The isolated ponds grew and coalesced rapidly to encompass an area of 160,000 $\pm$ 15,400 m^2 during 7-13 July (26% of the area inset in Figure 1); based on our topographic analyses, we ~~estimate~~ calculate a lake volume of ~~$1.36 \pm 0.19 \times 10^6$~~ $1.36 \pm 0.19 \times 10^6$ m^3 for this date. Drainage ~~had begun~~ began by 16 July, when we ~~estimate~~ calculate that the lake system's area and volume had reduced to 75,600 $\pm$ 11,100 m^2 and ~~$0.35 \pm 0.034 \times 10^6$~~ $0.35 \pm 0.034 \times 10^6$ m^3 (~~this estimate is based on~~ estimated with limited shoreline data; see Supplementary Material). The lake's area had stabilised by 17 July, leaving several isolated ponds containing 44,000 $\pm$ 15,000 m^3, which changed little thereafter in 2017 (Figure 1h-i).

Visual inspection of the Planet optical imagery and Pléiades DEMs reveals little change in the area immediately down-glacier of the lake following drainage. Near the terminus of Changri Shar, pronounced surface lowering was concentrated along the proglacial/supraglacial stream (Zone A~~in~~ ; Figure 2 and Table 1). Where this stream leaves the glacier system, it destabilised the northern side of Changri Shar's proglacial gorge (Figure 4), leading to a ~~large~~ ~6.0×10^4 m^3 landslide by 16 July (Zone B; Figure 4). The erosion in this area forced reestablishment of a major trail between Lobuche and Gorak Shep settlements on the ~~trek~~ route to Everest Base Camp.

On 16 July, the Changri Shar proglacial stream entry point into Khumbu Glacier was ~~clearly observed to be~~ buried by the ~~mixed~~ water and debris slurry from the initial outburst flood and the Zone B landslide. Based on the ~~observed~~ area of the inundated zone (32,700 m^2) and the March Pléiades DEM, we estimate a total volume of 2.56×10^5 m^3 impounded at the Khumbu entry on 16 July (Figure 4). By 17 July, the Changri Shar stream had incised through the ~~debris deposit~~newly-deposited debris, and large concentric crevasses had opened in Khumbu Glacier surrounding this point; field observations confirmed that these features ~~are~~ were still apparent in 2018. This area experienced a mean surface lowering of 6 m for the March-November period, totalling a volume loss of 1.86×10^5 m^3 despite the significant debris deposition, of which at least 32,900 m^3 remained in December (Zones C and D in Table 1).

There is little evidence of flood-induced surface change on Khumbu Glacier ~~relating to the drainage event until a point~~ until 2.8 km down-glacier from ~~this~~ the stream entry point. Here, some 2.3 km upstream of the Khumbu terminus, large zones of pronounced surface lowering and supraglacial channel migration are apparent in the dH map and 16-17 July orthoimages (Figure 5), and cannot be accounted for by pre-existing ice cliffs~~(Figure 5)~~. We interpret these to be collapse features ~~following~~ along the route of shallow englacial channels which were exploited by the floodwaters (Zones E-H; Figure 5). These zones of enhanced surface change continued to the Khumbu Glacier terminus and account for at least 4.53×10^5 m^3 of volume loss (Table 1). Field observations of the lower ablation area in April 2018 suggested that additional conduits collapsed and became exposed at the surface in this area through winter (> 9 months after the event), beyond the observation period of the March-November DEM difference.

~~The Khumbu Glacierproglacial stream system also underwent extensive changes~~ Khumbu Glacier's proglacial stream also changed extensively during 2016-2017, including widespread ~~patterns of~~ stream migration and bank erosion (Figure 6). During this period, the stream destabilised the moraine outlet, leading to small landslides (Zones I and J; Figure 6). Directly below the Khumbu outlet the proglacial stream overflowed its banks, leading to areas of considerable erosion and deposition (> 3 m dH) across the outwash plain (Zone K~~,~~; Figure 6). Below the outwash plain, the proglacial channel showed patterns of active channel migration and bank erosion between 16-17 July ~~and~~ at least as far as Pangboche~~(~~, 11 km downstream ~~), with~~ (analysis further down-valley was inhibited by deep terrain shadows). The total area affected by channel migration (52,700 m^2) for the 2016-2017 period is similar to total channel migration over 2012-2015 (Table 2), but the 2016-2017 period exhibits a ~~greatly magnified~~ much larger area of bank erosion (117,200 m^2 ~~vs~~ compared to 6,125 m^2).

The proglacial river stage record near Pheriche documented seasonal and diurnal variations in discharge (Figure 7~~, inset~~). Discharge was < 2 m^3 s^{-1} prior to June 2017, then stabilised at ~3 m^3 s^{-1} until the beginning of July (Figure 7b). Early July was characterised by greater variation in discharge, with daily peaks up to 10 m^3 s^{-1} ~~declining~~ decreasing into the middle of July. On 15 July, the discharge record departed from this general ~~decline~~ decrease in peak daily flow, and discharge progressively increased to peak at ~~56 ± 11~~ 56 ± 11 m^3 s^{-1} at 12:30 on 16 July (Figure 7a). Discharge decreased rapidly after 13:00 to a low value of 5.9 m^3 s^{-1} at 17:30, then again increased to 12.4 m^3 s^{-1} at 20:30. Measured discharge then decreased gradually to 2.9 m^3 s^{-1} at 10:00 on 17 July, and resumed a regular diurnal pattern with discharge varying between 3-7 m^3 s^{-1}. Based on our estimated baseflow, we calculated a total flood discharge of 0.97 ~~$\pm 0.23 \times 10^6$~~ $\pm\ 0.23 \times 10^6$ m^3 between 20:00 on 15 July and 10:00 on 17 July.

4 Discussion

4.1 Interpretation

The dynamics of the lake system formation are relatively straightforward to interpret. A significant obstruction to the coupled supraglacial and englacial drainage system must have formed during winter 2016-2017, as occurs seasonally for other debris-covered glaciers (Benn et al., 2017; Miles et al., 2017b). This may have been the consequence of a significant conduit collapse or freeze-on of accumulated englacial debris, as has been observed through glaciospeleology (e.g. Gulley and Benn, 2007; Gulley et al., 2009b)~~, but~~. However, the impediment to drainage ~~was~~ appears to have been unusually effective in early 2017, preventing the development of preferential flowpaths which would lead to increasingly efficient drainage. Thus, as winter snow in the ablation area melted due to the onset of pre-monsoon conditions, this water accumulated in a large surface depression opened over recent years by heightened ablation along supraglacial ponds and ice cliffs. The accumulated water would have had a positive surface energy balance through the pre-monsoon, leading to peripheral ablation and further increasing the depression capacity and lake volume (Sakai et al., 2000; Benn et al., 2001; Miles et al., 2016).

~~The~~ Supraglacial ponds initially grew in isolation, then coalesced ~~supraglacially~~ between 18 May and 17 June as the water levels rose (Figure 3). By 19 June, new peripheral ponds began to fill, suggesting the flooding of englacial conduits ~~to a distance of~~ up to 300 m away from the main water body. These secondary ponds mostly coalesced with the main surface water body before its eventual drainage. Based on the pond shorelines and Pléiades DEM, we estimate a steady water supply rate of 0.14 m^3 s^{-1} for 17 June to 13 July.

The ~~dynamics~~ process of pond drainage ~~are~~ is slightly less clear due to the lack of observations during 14-15 July. ~~Drainage of~~ The available PlanetScope imagery indicates that the lake began to drain between 13-15 July, and was still underway on 16 July~~according to the PlanetScope imagery~~. Given the total duration of the flood at Pheriche (~36 hours) and the landslide deposit ~~on the 16th~~identified on 16 July, we expect that drainage began around midday on 15 July. Based on the lack of down-glacier surface change on Changri Shar, ~~the lake must have~~ we infer that the lake drained englacially or subglacially~~;~~, rather than along the surface. Hydrofracture is an unlikely scenario as the ice is nearly stagnant in this area; rather, this could have been accomplished by penetrating the internal blockage or ~~via hydrofracture~~establishing a new connection to relict conduits. In either case the water reemerged at the surface ~~700~~ ~700 m away, just prior to the Changri Shar terminus.

The textureless appearance of the flooded entrance to Khumbu Glacier imaged on 16 July (Figure ~~3c~~4c) suggests that the water had only recently reached this position~~; this~~. This assessment is supported by the rapid subsequent drainage of the flooded water and incision of the debris deposit, which had occurred by 17 July. As this subsurface conduit would have closed at least partially ~~due to creep~~ since the prior monsoon, the sudden input of water and debris likely overwhelmed the conduit's capacity. Using an empirical relation for peak tunnel discharge ($Q_p = 46{V_p}^{0.66}$, with V_p the lake volume in 10^6 m^3; Walder and

Costa, 1996), we estimate a peak discharge of 59 m^3 s^{-1}. Some water may have been retained in ~~the~~ both glaciers' drainage network, and the flood at Pheriche is likely to have incorporated additional meltwater and debris along its glacial and proglacial flowpath, but this discharge estimate is very close to the maximum discharge of ~~56 ± 11~~ 56 ± 11 m^3 s^{-1} ~~observed at~~ measured by the Pheriche gauge.

As with Changri Shar, the lack of surface change on Khumbu Glacier suggests a subsurface flowpath for much of the glacier's length. However, the floodwaters appear to have reached the glacier surface 2.3 km from the terminus, where several segments of conduit collapse are evident~~; this is in partdue to the heightened~~. We interpret this as due, at least in part, to the elevated hydrological base level of Khumbu Glacier (Gulley et al., 2009a), whose terminus area has experienced extensive ponding in recent years (Watson et al., 2016).

~~The contrast in~~ There is a notable contrast in the magnitudes of proglacial stream migration and bank erosion ~~magnitudes~~ between the 2012-2015 and 2016-2017 periods ~~is clear~~ (Table 2). ~~As evidenced by~~ During the 2012-2015 period, channel migration ~~is~~ was a continuous background process ~~, but largely stays~~ that predominantly remained within the stream banks. This period ~~encompasses~~ encompassed the Gorkha earthquake (Kargel et al., 2016), which would have ~~enhanced~~ increased debris supply and stream migration. ~~Outburst floods from Imja Khola during 2015 and 2016 (Rounce et al., 2016) may also have affected landscape change below Pheriche. However, the~~ The 2016-2017 NDWI and NDVI changes show a greater magnitude of channel migration than 2012-2015, despite the shorter time interval. The area of bank erosion is ~~greatly magnified~~ also greatly enhanced during 2016-2017~~, and examining available historic satellite image archives we have not found an image of this area in similar conditions, suggesting this~~. The magnitude of geomorphic change ~~is uncommon~~associated with the flood appears to be uncommon, since we were unable to find similar areas of bank erosion in any of the historic satellite image archives.

The double peak of discharge observed at Pheriche (Figure 7) is unusual for outburst floods. ~~One~~ A possible cause is the blockage of the Khumbu stream inlet by the landslide in the Changri Shar proglacial gorge (Figure 4). This is likely to have initiated around peak flow through the gorge, and ~~would~~ could have led to a ~~precipitous~~ substantial decline in discharge, followed by a later, sudden increase as preferential flowpaths developed through the debris (Gulley et al., 2009b). ~~Alternatively, it is possible that the heightened~~ A second explanation is the possibility of multiple flowpaths for the flood through the lower part of Khumbu Glacier. As Khumbu Glacier exhibits a low terminus slope and high hydraulic base level, the flood may have temporarily overwhelmed the subsurface drainage network and, exploiting fractures and secondary pathways common for these glaciers, partially emerged at the glacier surface. This would result in two or more flowpaths of differing efficiency, possibly leading to distinct discharge peaks on the Pheriche hydrograph. This possibility is supported by the appearance of highly turbid water in the ponds between zones E-G (Figure 2) during drainage. A third possibility is that the increased discharge late on 16 July corresponds to delivery of ~~other water stored~~ water stored elsewhere within the glacier system. Such stored water might connect to the drainage system more efficiently by the opening of conduits and channels during the flood. ~~It~~ Regardless, it is clear that the ~~heightened~~ increase in discharge at Pheriche only lasts until 10:00 on 17 July, so ~~either mechanism had a~~ the flood's direct contribution to discharge was short-lived~~influence on the glaciers'overall discharge~~.

4.2 Implications

The ~~utility of novel observational~~ use of novel satellite platforms for observing and interpreting this event ~~is noteworthy, and this supraglacial lake drainage and subsequent outburst has~~ enabled development of a detailed chronology of surface changes rarely available for such events. Our observations of the drainage and outburst of the Changri Shar supraglacial lake have several implications for cryospheric hazards and debris-covered glacier hydrology. First, this is ~~an extremely~~ a short-lived event, with a lake system of 1.36×10^6 m^3 ~~(544 Olympic swimming pools)~~ filling and draining within one ablation season. This is important because despite the lake's short duration and relatively small volume, the event led to considerable glacial, fluvial, and geomorphic change~~, and forced diversions of~~. These changes disrupted major trails, which are the primary corridor for local trade and tourism, in at least three locations ~~(Figures 2, 5 and 6; Watson et al., 2018)~~(Figures 2, 5 and 6; Watson and King, 2018). As suggested by Komori et al. (2012) and Narama et al. (2018), the hazard posed by such features is ~~non-negligible~~significant, yet traditional glacial lake monitoring approaches, which rely on repeat optical imagery such as Landsat and Sentinel-2, would have had difficulty observing the lake's formation ~~at all~~ due to the timing of repeat passes and cloud cover. Considering all Landsat 8 or Sentinel-2 scenes over the period of our analyses, we find only two that are mostly cloud-free over the supraglacial lake in the two months leading up to lake drainage. Pond observations during the monsoon are intermittent at best (Watson et al., 2016; Miles et al., 2017a) and thus we recommend the adoption of high-frequency repeat optical imagery (as in this study) and Synthetic Aperture Radar data products (e.g. Strozzi et al., 2012) for improved monsoon monitoring of glacier hydrology.

Furthermore, the ~~limited seasonal observations (biased to~~ scarcity of seasonal observations of glacier hydrology (limited to a few closely monitored glaciers) suggest that short-lived or seasonal outburst floods may be a regular feature for debris-covered glaciers in the region. This is important because ~~in both the cases of~~ both Rounce et al. (2017) and this study ~~,~~ indicate that outburst floods from sources other than large proglacial lakes have had downstream effects on ~~the~~ transportation networks and the livelihoods of local communities. The ~~several observations of seasonal outburst floods are suggestive of~~ few observations of outburst floods from high-elevation debris-covered glaciers suggest a distinct seasonal cycle of hydrological development ~~for debris-covered glaciers as compared to~~ that contrasts with clean ice glaciers (e.g. Fyffe et al., 2015; Miles et al., 2017a; Narama et al., 2017). Rather than a gradual up-glacier progression of an efficient, connected drainage network (e.g. Nienow et al., 1998), ~~these~~ debris-covered glaciers may impound significant volumes of water internally and at the surface before establishing efficient drainage through the lowest portion of the glacier (Miles et al., 2017c). This key difference is likely related to the melt-inhibiting thick debris ~~low~~ near the terminus on such glaciers, which reduces the terminus area's sensitivity to seasonal warming. Instead, the zone of maximum melt (and seasonal sensitivity) is usually in the middle of the ablation area, leading to significant meltwater generation before efficient drainage pathways have been established for the lower glacier (Benn et al., 2017).

~~Nevertheless, the geomorphic evidence~~ The geomorphic evidence from this study suggests that supraglacial lake outburst floods of this magnitude are not particularly common in the Khumbu catchment (indeed, no large supraglacial lake ~~is forming~~ formed on Changri Shar in 2018, and past years show no evidence of such a lake). Still, supraglacial water storage is increasing for many Himalayan glaciers (e.g. Thompson et al., 2012; Watson et al., 2016). This is expected as climate warms and debris-covered glaciers stagnate, precursors to proglacial lake formation (Benn et al., 2012). In the case of Changri Shar, a very large closed surface depression had been opened by ice cliffs and supraglacial ponds prior to this event, creating the ~~storage capacity for the~~ capacity to store 1.36×10^6 m^3 ~~lake we observe~~of water. Consequently, as the excavation and pitting of near-stagnant debris-covered glacier termini by ice cliffs and supraglacial ponds becomes more prevalent with a warming climate, other glaciers in the ~~regional may accumulate~~ region are likely to develop large supraglacial water bodies. While the coalescence of ponds to form a large supraglacial lake represents an early stage of base-level lake development (Watanabe et al., 2009; Benn et al., 2012), such supraglacial lakes also ~~outburst~~ represent an outburst risk (as evidenced here). Thus, the expected increase in moraine-dammed glacial lake outburst floods due to a lagged response to climate warming (Harrison et al., 2018) may also apply to the outburst of supraglacial water bodies, and events similar to the Changri Shar outburst ~~may become more commonplace~~are likely to increase in frequency.

Finally, the rapid transit time we observe for the flood's passage of the lower Khumbu Glacier suggests that the glacier's subsurface drainage system ~~can adapt~~ has, or can develop, an efficient configuration ~~given sufficient water inputs~~in response to sufficient water supply. We base this assessment on the sudden interruption of peak discharge observed at Pheriche, which most likely corresponds to the blockage of the Changri Shar stream portal as observed in the PlanetScope image on 16 July (Figure 4c). This image was captured at 09:50, implying a transport time of 3-5.5 hours for water to travel a (straight-line) distance of 4.9 km through Khumbu Glacier. Consequently, we estimate a ~~conservative~~ mean travel velocity of at least 0.25-0.45 m s^{-1}; the water also passed 4 km from the glacier to Pheriche during this time ~~. Prior dye-tracing~~ but we cannot determine its transit time. Prior dye tracing studies have considered flow velocities > 0.2 m s^{-1} to indicate hydraulically efficient drainage through a system of major channelised conduits (e.g. Hubbard and Glasser, 2005), which we ~~interpret to be the case~~ thus interpret for drainage through Khumbu Glacier during this event. ~~It is likely that subsurface drainage~~ The subsurface drainage initially exploited a preexisting marginal flowpath maintained by normal discharge from Changri Shar and Changri Nup Glaciers, ~~as~~ similar to that inferred for Ngozumpa Glacier by Benn et al. (2017), thus enabling the system's rapid ~~adaptation to~~ accommodation of the surplus water. It appears that subglacial or deep englacial flowpaths were utilised by the flood for ~~both Changri Shar~~ Changri Shar Glacier (~700 m subsurface transit) and much of Khumbu (2.8 km subsurface transit) ~~glaciers, largely bypassing the coupled supraglacial-englacial~~ Glacier. The outburst seems to have bypassed the coupled supraglacial and shallow englacial drainage networks inferred by Irvine-Fynn et al. (2017) and Miles et al. (2017b) ~~.~~ until the lowermost portion of Khumbu Glacier, where at least some water emerged at the surface and routed through the terminal chain of ponds. Our interpretations of hydraulically efficient subsurface drainage and subsurface-to-surface routing reflect the response of the drainage system to flood conditions, so additional observation is needed to understand the structure of the drainage system with normal meltwater inputs.

5 Conclusions

We ~~applied high resolution satellite remote sensing~~ analysed high-resolution satellite imagery to document and interpret the rapid formation, drainage, and outburst of a supraglacial lake system on Changri Shar Glacier in the Everest region of Nepal. The lake filled ~~in ~3 months to encompass~~ between April and July 2017 to an area of 180,000 m^2 and volume of 1.36×10^6 m^3 prior to drainage, likely beginning on 15 July. The flood ~~appears to have~~ passed primarily through the subsurface of both Changri Shar and Khumbu glaciers. With a peak discharge of 56 ~~±11~~ ± 11 m^3 s^{-1} observed 4 km downstream and minimum glacier transport velocities of 0.25-0.45 m s^{-1}, the event ~~is suggestive of~~ suggests an efficient subsurface drainage ~~system configuration largely bypassing the coupled supraglacial-englacial systems common to hummocky debris-covered glaciers. The~~ of the flood for most of its flowpath. Where routed to the surface on the lowermost portion of Khumbu Glacier, the floodwaters led to the collapse of shallow englacial conduits between supraglacial ponds. In addition, the outburst flood led to substantial geomorphic change ~~for~~ of both the Changri Shar and Khumbu proglacial systems, and forced rerouting of major trails in the area. We expect that outburst floods of this type and magnitude are not common, but ~~may~~ will increase due to climate warming and ~~consequent~~ glacier recession.

Our observations of lake dynamics were only possible through the use of rapid-repeat high-resolution imagery, and similar approaches should be used to document monsoon-season hydrology of debris-covered glaciers, which is largely unobservable by ~~traditional~~ optical satellite sensors. There is evidence for dynamic changes to these glaciers' drainage systems during the monsoon and for the occurrence of seasonal outbursts of lower magnitude~~as a common feature~~. Nonetheless, there remains a considerable need for systematic, robust observations of debris-covered glacier hydrology, as these glacier systems exhibit distinct storage components and seasonal drainage development patterns relative to clean ice glaciers. This is a crucial observational gap, as the hydrological storage and discharge of debris-covered glaciers has significant consequences for glacial hazards, surface ablation, glacier dynamics, proglacial sediment dynamics, and water supply with direct ~~effects~~ impacts on downstream populations.

Data availability. All derivative data used in this study (lake coverages, dH zones) are available upon request. Please contact Evan Miles for this purpose (evan.miles@wsl.ch). PlanetScope and RapidEye data are freely available in reasonable quantities for research and education, see https://www.planet.com/markets/education-and-research/.

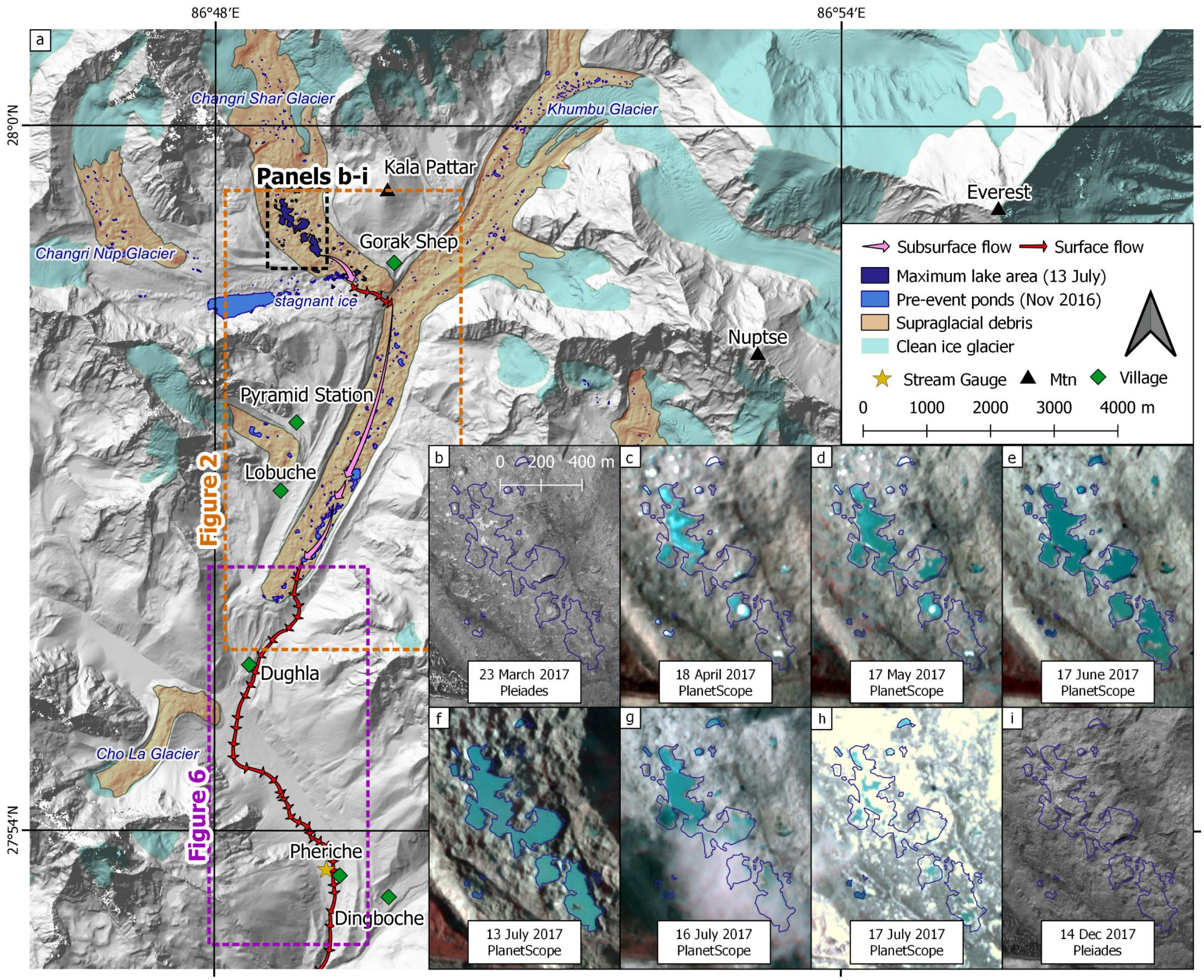

Figure 1. The study area and interpreted flow path through Changri Shar and Khumbu Glaciers ~~, and the~~ (a). The expansion and drainage of the Changri Shar supraglacial lake in ~~2017.~~ 2017, denoting maximum observed lake area with an outline (b-i). Debris-covered glacier area was delineated manually with respect to the March Pléiades imagery, and modified from the RGI 6.0 (Pfeffer et al., 2014). The background hillshade is ~~a composite~~ derived from ~~Pléiades (this study) and WorldView sources (Shean et al., 2016)~~the High Mountain Asia DEM mosaic (Shean, 2017).

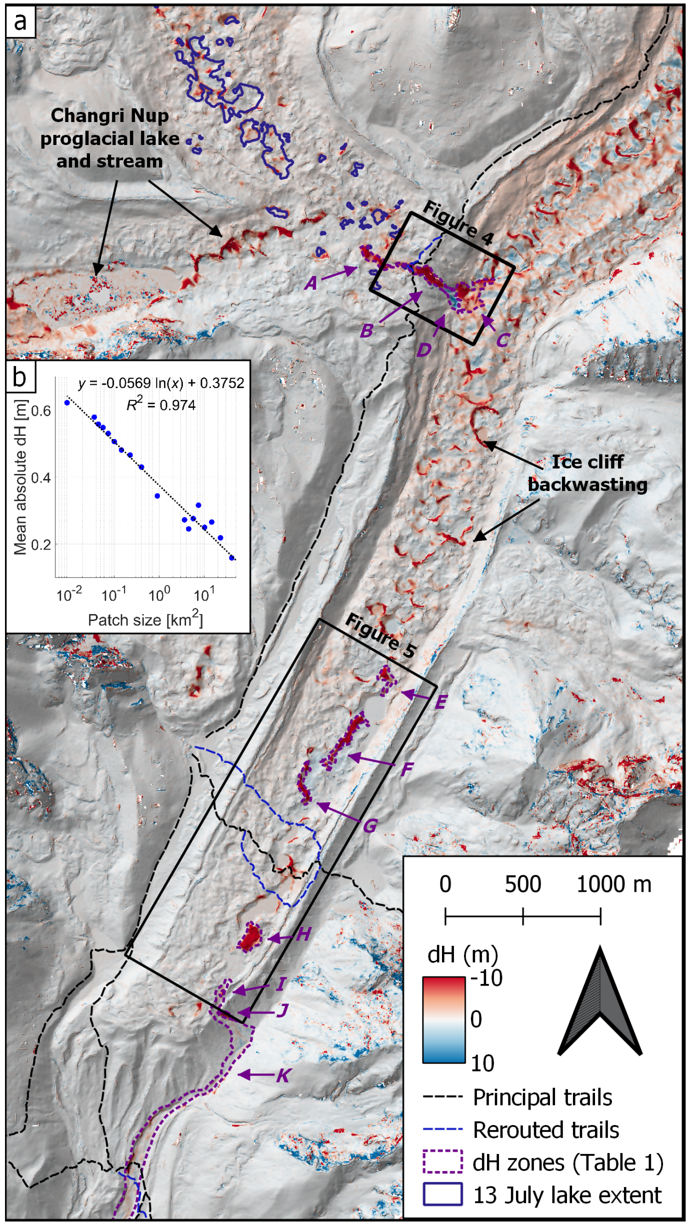

Figure 2. Zones A-K (purple labels) of ablative and geomorphic change associated with the lake drainage as measured by Pléiades March-December DEM differencing, with ~~context~~ extent of Figures 4 and 5 indicated (a). Error assessment for March-December 2017 Pléiades DEM difference (b).

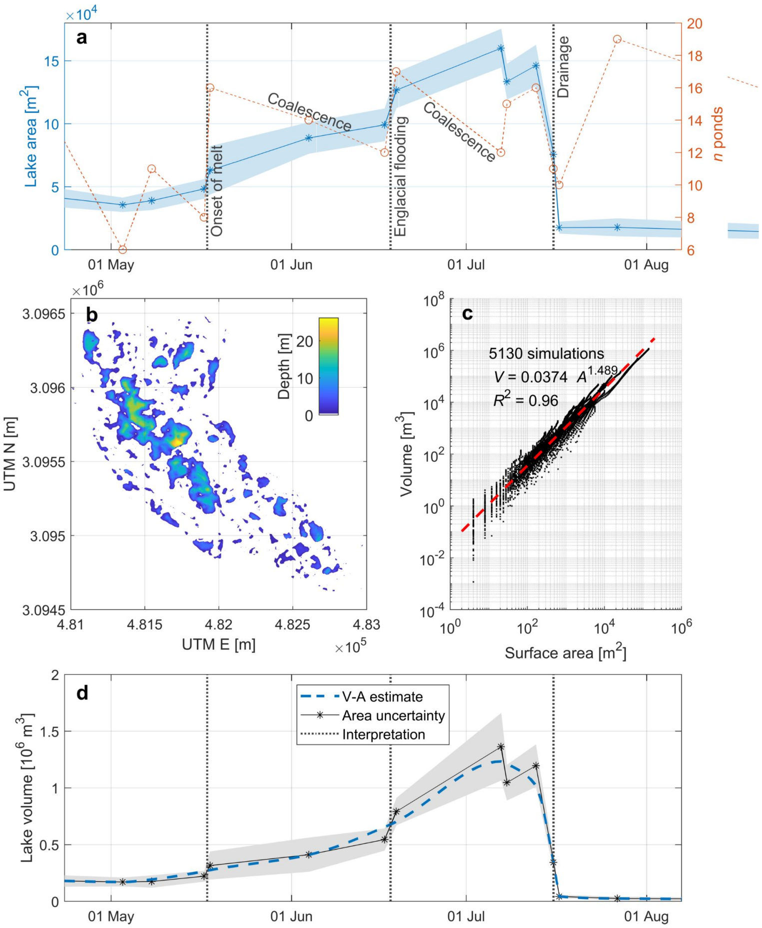

Figure 3. Total lake area and number of individual water bodies ~~within the area of the insets in Figure 1~~ during the supraglacial lake's expansion and drainage ~~, expressing areal~~ (within the area shown in Figure 1b-i). Area uncertainty ~~with~~ is represented by a ±1-pixel buffer (a). ~~An analysis of the~~ The depth of closed surface depressions on Changri Shar Glacier derived from the March 2017 Pléiades DEM (b) ~~was used to determine the~~ and their volume-area relationship ~~for the study area~~ (c). We used this relationship to reconstruct the lake system's volume prior to drainage (d).

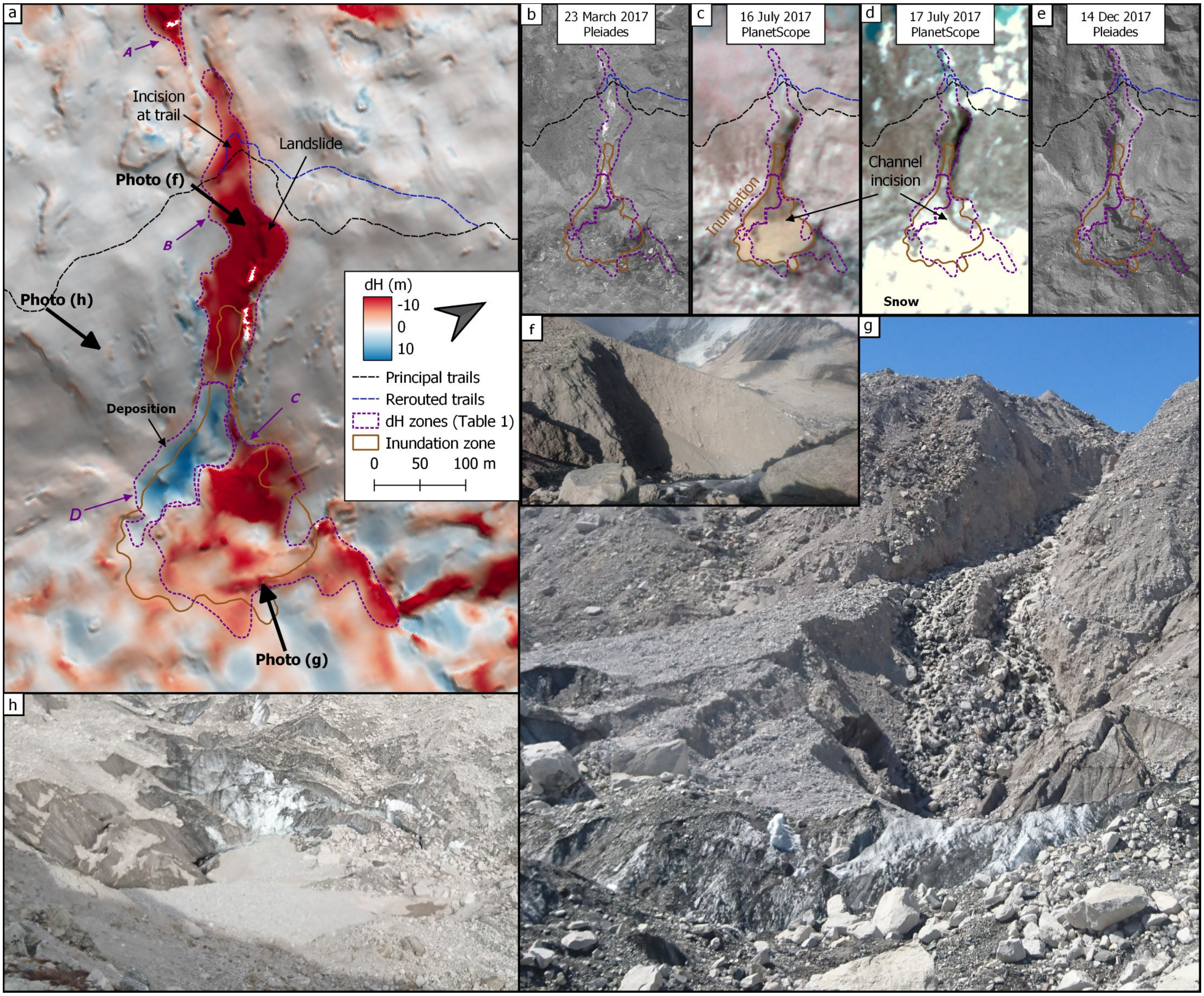

Figure 4. ~~Surface elevation changes~~ Flood-related geomorphic evidence at the base of the Changri Shar proglacial gorge~~, also indicating~~. Surface elevation changes and locations ~~for~~ of selected field photos, with hillshade of March Pléiades DEM as background (a). ~~Panels (b-e) document~~ Time series of satellite images documenting the blockage and incision of the stream inlet to Khumbu Glacier, with date and source specified in the text box (b-e). A photograph taken in May 2018 of a fresh landslide scarp near the top of the proglacial gorge, the likely source for much of the debris (f)~~, as viewed in May 2018. The~~. A photograph of the deposit and incised channel~~as viewed~~, taken in October 2017 from the Khumbu Glacier surface (g)~~in October 2017. The~~. A photograph of the deposit and concentric crevassing ~~as viewed~~ taken from the Khumbu moraine in October 2017 (h). All photographs taken by the authors.

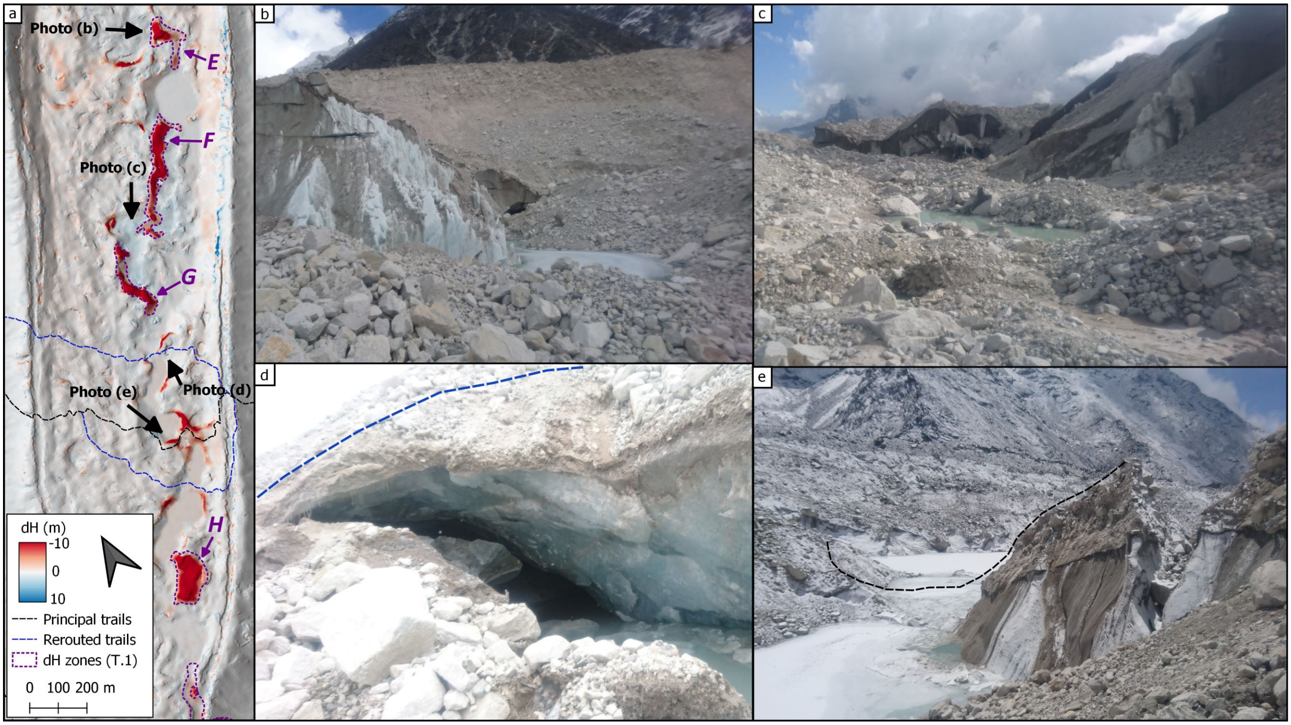

Figure 5. ~~Surface changes~~ Flood-related geomorphic evidence on Khumbu Glacier. Surface lowering, rerouting of the Kongma La trail, zones of analysis (Table 1), and positions of ~~select~~ selected photos of enhanced change over the ~~lowest~~ lowermost three km of Khumbu Glacier, with hillshade of March Pléiades DEM as background (a). The area of a conduit collapse (Zone E), with visible water flowing towards the exposed conduit entrance (b). A zone of fluvially-reworked debris directly located down-glacier from the conduit collapse in Zone F, and leading to exposed shallow conduits in the background (c). A cavernous englacial conduit exposure directly beneath the rerouted Kongma La trail (d). The route of the pre-event Kongma La trail, now cut off by a fresh conduit collapse (e, at right) and coalescing ponds. ~~Photos from~~ All photographs taken by the authors in May 2018.

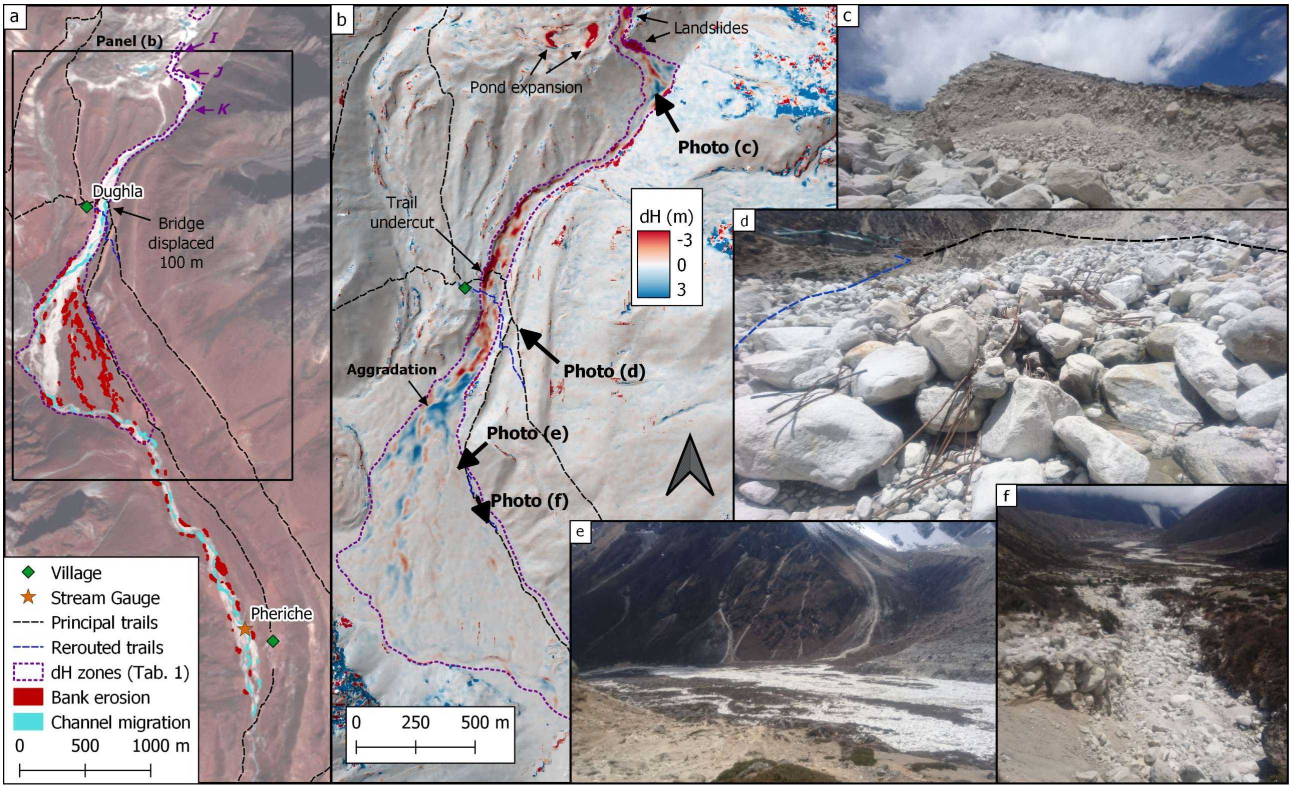

Figure 6. ~~Geomorphic effects~~ Flood-related geomorphic evidence down-valley of ~~the outburst flood below~~ Khumbu Glacier~~showing extensive~~. Extensive changes in vegetation cover due to bank erosion and migration of the stream channel 4 km downstream to Pheriche (a). Surface lowering associated with fluvial erosion and aggradation in the Khumbu proglacial system, and locations ~~for select~~ of selected photos (b). A fresh landslide scarp (Zone J) directly below the Khumbu outlet (c). Remnants of a pedestrian bridge destroyed, carried 100 m downstream, and buried by the outburst, also indicating route of the trail before and after the outburst, with Dughla in the background (d). The Khumbu outwash plain in May 2018, showing widespread fluvially-reworked debris (e). A secondary channel used by the outburst flood, leading to > 1 m incision (f). Background in (a) is a RapidEye false-colour composite from November 2016 and in (b) is the hillshade derived from the March 2017 Pleiades DEM.

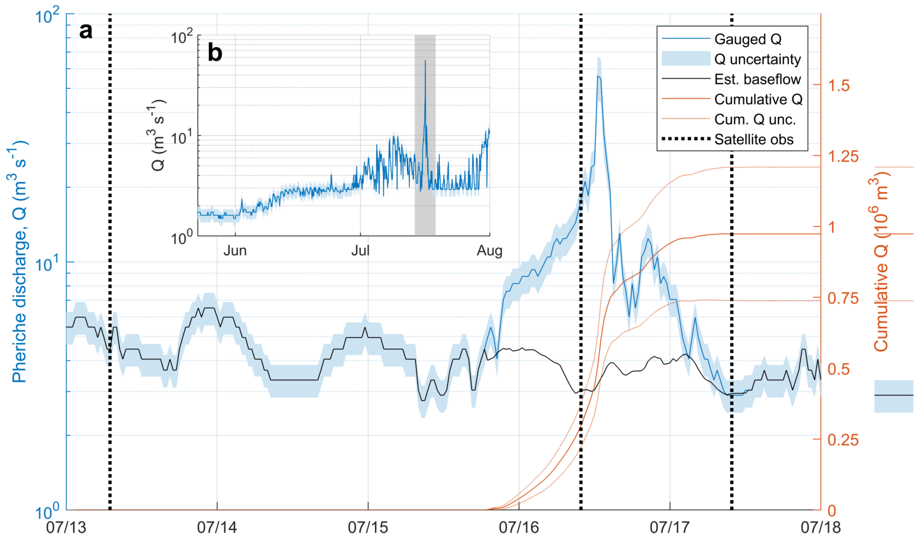

Figure 7. Pheriche discharge record during the outburst flood and cumulative flood volume, also indicating timing of PlanetScope observations (a). ~~Inset shows the~~ The discharge record throughout the 2017 monsoon (b). Note the log scale for discharge in both panels.

Table 1. Measured elevation changes associated with the lake drainage and outburst within key zones identified with the Pléiades stereo-imagery. CS and Kh denote Changri Shar and Khumbu Glaciers, respectively. Zones are identified in Figure 3. Δ V expresses the total volumetric change in each zone, and the full uncertainty based on σ_{dH} for the zone area. 'V added' and 'V removed' are based on the elevation changes exceeding σ_{dH}. $\overline{dH}$ is the mean change in elevation within the zone, with uncertainty σ_{dH}.

Zone	Description	Area (m^2)	Δ V (m^3)	V added (m^3)	V removed (m^3)	$\overline{dH}$
A	Emergence at CS terminus	10,020	-107,~~050~~100 ± 6,~~380~~ 400	0	-107,~~050~~ 100	-10.7 ~~±~~
B	Landslide and erosion in CS proglacial gorge	16,030	-186,~~030~~000 ± 9,~~780~~ 800	~~50~~ 100	-186,~~080~~ 100	-11.6 ~~±~~
C	Surface lowering at Kh entrance	27,870	~~-185,970~~ -186,000 ± 16,~~130~~ 100	400	-186,~~330~~ 300	-6.7 ~~±~~
D	Sediment deposition at Kh entrance	8,560	32,~~710~~700 ± 5,~~530~~ 500	32,900	-300	3.8 ~~±~~
E	Kh conduit collapse 1	9,400	-49,~~090~~100 ± 6,~~030~~ 000	~~150~~ 200	-49,~~110~~ 100	-5.2 ~~±~~
F	Kh conduit collapse 2	18,770	-149,~~660~~700 ± 11,~~290~~ 300	~~130~~ 100	-149,~~670~~ 700	-8.0 ~~±~~
G	Kh conduit collapse 3	9,900	-88,~~130~~100 ± 6,~~320~~ 300	~~40~~ 0	-88,~~130~~ 100	-8.9 ~~±~~
H	Kh conduit collapse 4	16,820	-167,~~050~~500 ± 10,~~220~~ 200	~~20~~ 0	-167,~~010~~ 000	-9.9 ~~±~~
I	Landslide 1 at Kh outlet	670	-4,200 ± ~~530~~ 500	0	-4,200	-6.3 ~~±~~
J	Landslide 2 at Kh outlet	2,860	-21,~~280~~300 ± ~~2030~~ 2,000	0	-21,~~270~~ 300	-7.4 ~~±~~
K	Kh outwash plain and proglacial channel	831,830	-80,~~210~~200 ± 320,~~080~~ 100	112,~~860~~ 900	-180,~~890~~ 900	-0.10 ~~±~~

Table 2. Areal changes along the Khumbu proglacial stream preceding (2012-2015) and encompassing (2016-2017) the lake outburst. Channel migration refers to the change in wetted area determined by NDWI thresholding, and bank erosion corresponds to the removal of vegetation in the channel area, identified by large NDVI differences.

Distance from	Area of channel migration (m^2)		Area of bank erosion (m^2)	
Khumbu outlet (km)	2012-2015	2016-2017	2012-2015	2016-2017
1	0	1825	0	275
2	0	8325	0	5500
3	6225	4000	0	66800
4	3300	7050	0	10650
5	1175	6600	0	17475
6	4700	4925	1300	4000
7	3775	2475	1600	2100
8	5125	7725	425	6125
9	900	6150	2250	2425
10	0	0	350	0
11	7600	3625	200	1850
Total	32800	52700	6125	117200
Change threshold	≥ 0.081	≥ 0.083	≤ -0.160	≤ -0.185

Author contributions. ESM and DJQ planned the study. ESM analysed the supraglacial lake area timeseries, analysed glacial and proglacial elevation changes, and led the manuscript writing. CSW analysed proglacial stream migration and bank erosion. FB and EB processed the Pléiades tri-stereo imagery and coregistered DEMs and orthoimagery. ME installed, calibrated and collected data from the Pheriche stream gauge. ESM, KEM, and DJQ conducted fieldwork to assess and interpret geomorphic changes. All authors contributed to the interpretation of changes and manuscript preparation.

Competing interests. The authors declare that they have no conflict of interest.

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