Supraglacial pond evolution in the Everest region, central Himalaya, 2015-2018.

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Abstract

Supraglacial ponds are characteristic of debris-covered glaciers and can greatly enhance local melt rates. They can grow rapidly and coalesce to form proglacial lakes, presenting a major hazard. Here, we use Sentinel-2A satellite imagery (10 m) to quantify the spatiotemporal changes of 6,425 supraglacial ponds for 10 glaciers in Everest region of Nepal between 2015 and 2018. During the study period, ponded area increased on all glaciers, but showed substantial temporal and spatial variation. The rate of pond growth accelerated compared to 2000-2015 (Watson et al., 2016). Both Imja and Spillway Lake expanded and Khumbu Glacier continued to develop a chain of connected ponds. 54% of ponds were associated with an ice-cliff, but the proportion of ponds with cliffs decreased during the study period. Pond location showed limited correspondence to slope, but favoured areas of lower surface velocity. Ideal conditions for pond formations have advanced up-glacier, and are now predominantly found at mid-elevations. Results indicate high-resolution imagery (< 10 m) is essential, as using Landsat data would miss 55–86 % of the total ponds found. Finally, glaciers were classified by stage of development (Komori, 2008; Robertson, 2012), with two transitioning between 2015 and 2018, suggesting lakes in the region are evolving rapidly. Furthermore, some glaciers displayed characteristics of multiple classes, so we propose an adapted classification system. Overall, our results demonstrate a trend of pond expansion in the Everest region and highlight the need for continued monitoring for hazard assessment.

Key Words: *Supraglacial ponds, remote sensing, outburst floods, hazards.*

1. Introduction

Mass loss from glaciers in the Himalayas has increased rapidly over the past 30 years, in response to climate change (e.g. Bolch et al., 2012; Kääb et al., 2012; Quincey et al., 2009; Gardelle et al., 2013). Here, 'summer-accumulation type' glaciers rely on summer-monsoon snowfall for mass gain (Bolch et al., 2012), which is thought to be reducing as temperatures rise (Fujita, 2008). The shrinkage of these freshwater reservoirs will have significant regional- and local-scale impacts (Immerzeel et al., 2010; Bolch et al., 2012; Dehecq et al., 2018). Seasonal monsoonal rainfall is the dominant source of water in the Himalaya, but glacial meltwater provides up to 40% of water supplies during the dry season (Immerzeel et al., 2010). Thus, the consistent negative mass balance of Himalayan glaciers may lead to long-term reductions in perennial flow supplied to major rivers outside of monsoon season (Xu et al., 2009), and could threaten the water and food security of an estimated 70 million people in the densely populated downstream catchments (Immerzeel et al., 2010). Additionally, increased supraglacial meltwater storage will likely increase the frequency of glacier related hazards in the region, particularly from Glacier Lake Outburst Floods (GLOFs) (Thompson et al., 2010). GLOFs are highly destructive and Nepal (along with Bhutan), has been identified as the most economically vulnerable to these hazards (Carrivick and Tweed, 2016), making it vital to assess how the GLOF risk will evolve with climate warming.

The Everest region comprises three catchments spanning the Nepal/Tibet border in Eastern Nepal (Fig. 1; King et al., 2017). These catchments have experienced atmospheric warming since the mid-1970's (Shrestha et al., 1999; Shrestha and Aryal, 2011) and weakened summer monsoons, which has reduced glacier accumulation (Salerno et al., 2015). Consequently, glacial mass balance in the region has been strongly negative since the 1970s (Bolch et al., 2008; Benn et al., 2012; Kääb et al., 2012). For example mass balance in the Everest Region of Nepal was -0.22 ± 0.12 m w.e.a^{-1} between 1999 and 2011 (Gardelle et al., 2013). Glaciers in the Everest region are characterised by ice-surface rock debris, which is sourced from the surrounding hillslopes and covers approximately ~80% of the glaciated area in the region (Fushimi et al., 1980; Sakai et al., 2000; Watson et al., 2016). The presence of this surface debris substantially alters the glacier mass balance gradient, in comparison to clean-ice glaciers: melt is supressed close to the termini, due to the presence of thick debris which insulates the underlying ice, and enhanced up glacier, where debris is thinner and increases melt (e.g. Quincey et al., 2009; Nicholson and Benn, 2013). As a result, the glaciers are characterised by high elevation accumulation areas, and lower-elevation ice tongues, which have low surface slopes and are near-stagnant, due to the low driving stresses (e.g. Bolch and Kamp, 2006; Quincey et al., 2009; Bolch et al., 2011; Dehecq et al., 2015). Consequently, glaciers in the Everest region lose mass by widespread surface lowering (i.e. down-wasting), rather than through terminus retreat (Quincey et al., 2007; King et al., 2017).

The low surface slopes and slow ice velocities that characterise debris-covered glacier tongues in the Everest region (Quincey et al., 2007; King et al., 2017), and the Himalaya more broadly (e.g. Kääb, 2005) facilitate supraglacial pond formation, by allowing glacial meltwater and rainfall to accumulate in depressions on the glacier surface (Reynolds, 2000; Sakai et al*.,* 2000; Miles et al., 2016 and 2017). These ice surface lakes can then coalesce to form a larger proglacial lake, which carries the risk of producing GLOFs (e.g. Richardson and Reynolds, 2000; Quincey et al., 2007; Thompson et al., 2012; Mertes et al., 2017). Supraglacial ponds are highly variable in character (e.g. in shape, size, turbidity and ice-cliffs), dynamic in nature, and are expected to become increasingly prevalent in a warming climate (Thompson et al., 2016; Miles et al., 2017; Watson et al., 2016; 2017a and 2017b).Understanding the spatial and temporal patterns of pond growth is therefore vital for accurately forecasting proglacial lake growth and the associated hazard of GLOFs (Richardson and Reynolds, 2000; Quincey et al., 2007; Benn et al., 2012).

As well as posing a hazard through the formation of proglacial lakes, supraglacial ponds represent hotspots for ablation on low-gradient debris-covered tongues (Miles et al., 2017; Watson et al., 2017a and 2017b). This is because they have a comparatively low albedo and therefore absorb more insolation, which they transmit to surrounding ice, resulting in higher melt rates (e.g. Reynolds, 2000; Benn et al., 2001; Röhl, 2008; Miles et al., 2016; Watson et al., 2016; Mertes et al., 2017; Salerno et al., 2017). These enhanced melt rates cause the ponds to expand both horizontally, through subaerial and sub-aqueous melting at the margins, and vertically, via basal melting (e.g. Sakai et al., 2000; Röhl, 2008; Mertes et al., 2017). Variations in the spatial distribution of ponds across a glacier is thought to be governed by surface slope and velocity (e.g. Reynolds, 2000; Bolch et al., 2008; Quincey et al., 2009), and results in differential surface melt rates (Sakai et al., 2000; Benn et al., 2001; Miles et al., 2016; Watson et al., 2016; Mertes et al., 2017). Once formed, ponds can persist for months to years, or drain via englacial pathways (e.g. Immerzeel et al., 2014; Miles et al., 2017; Watson et al., 2017a). Patterns of pond drainage are generally governed by their interaction with crevasses and englacial features, which provide efficient drainage outlets (Benn and Lehmkuhl, 2000; Miles et al., 2017). Determining whether ponds drain regularly or persist is important, because long-duration ponding can cause substantial ice-surface melt, whereas repeated pond drainage events can convey energy into the glacier's interior (Miles et al., 2017), resulting in quite different ice loss patterns. Additionally, recent studies (e.g. Brun et al., 2017; Buri et al., 2016; Mertes et al., 2017; Watson et al., 2017b) suggest that ice-cliffs play a significant role in pond formation, by enhancing marginal pond melt and subaerial calving. Furthermore, as ponds expand, ice and debris influx into the pond from retreating cliff-tops increases, causing pond turbidity to increase and subsequently reducing albedo, initiating a positive feedback of melt (Mertes et al., 2017). These factors complicate predicting future supraglacial pond formation and evolution and make them highly dynamic features.

Previous studies have documented changes in supraglacial water storage across the Himalaya (Table 1; e.g. Wessels et al., 2002; Kattlemann, 2003; Bajracharya and Mool, 2007; Gardelle et al., 2011). However, the use of comparatively coarse resolution imagery (e.g. 30m resolution Landsat imagery and 15m resolution ASTER imagery) means substantial water volumes may be missed and the low repeat frequency makes differentiating between pond persistence and regular drainage difficult, which is important for quantifying the impact of the ponds on mass loss (Immerzeel et al., 2014; Miles et al., 2017). Watson et al. (2016), presented the first high temporal and spatial resolution study of supraglacial pond evolution in the Everest region, for the period 2000-2015, where a total of 9340 ponds were identified. Here, we extend this previous work to quantify supraglacial pond evolution between 2015 and 2018. This will provide an up-to-date picture of pond coverage within the region. Our main objectives are; (1) characterise the spatial and temporal evolution of supraglacial ponds, to determine the magnitude and extent of change since 2015, (2) assess the impacts of using higher resolution imagery versus lower resolution imagery on the ability to identify and assess supraglacial ponds (3) examine the impact of local glacier characteristics (glacier surface slope, ice velocities and the presence of ice cliffs) on pond formation location, area and number and (4) classify the stage of proglacial lake development across the region.

2. Methods

2.1 Study Site and Water-body Definitions

The study focuses on ten debris-covered glaciers that drain the Dudh Koshi basin, within Sagarmatha National Park, Eastern Nepal (Fig. 1). The glaciers flow predominantly in a southerly direction, with the exception of Ama Dablam (north flowing) and Imja (west flowing) glaciers (Fig. 1). All of the study glaciers have extensive debris-covered tongues and high accumulation areas. Ngozumpa, Pangbung and Khumbu glaciers have the greatest length (~15 km, ~13 km and ~11 km respectively) and Imja Glacier the shortest at ~2 km (Table 2). Of the 10 glaciers in this study, 8 were also included in Watson et al. (2016) study for the period 2000-2015 (Table 2). We add Pangbung Glacier and Sumna Glacier to our study, as they are important for downstream water resources and could potentially pose a threat to downstream communities due to GLOFs (Immerzeel et al., 2010). The distinction between glacial 'pond' and 'lake' remains poorly defined in the Himalayan literature, with Watson et al. (2016) referring to all surface water as ponds unless specifically named otherwise, and other authors switching between the terms 'lake' and 'pond' (e.g. Gardelle et al., 2011; Nie et al., 2013). Here, we use the term pond to refer to all bodies of water on the glacier surface. Proglacial lakes are discussed separately from ponds, and are defined as all water bodies that are outside of the glacier margin, but are in contact with it. Following this classification, 'Spillway Lake', located at the terminus of Ngozumpa Glacier, is classified as a pond as it remains bound by glacier ice on all sides, but here is discussed separately, as its very large area would skew results. Imja Lake, located at the front of the Imja/Lhotse Shar glacier complex is classed as a proglacial lake.

2.2 Data Sources

This study used true-colour orthorectified Sentinel 2A imagery (<10 m resolution) (available from USGS at http://earthexplorer.usgs.gov/) for the time period December 2015 to April 2018 (SI. Table 1). Images outside of the monsoon season (June-September) were chosen, to minimise cloud cover and where possible, images were selected from the same month to avoid inadvertently including seasonal differences into our analysis (SI. Table 1). True colour images were derived from combining the blue (490 nm), green (560 nm) and red (665 nm) bands. For each of the study years, two true-colour Sentinel-2A images from the same date were mosaicked to produce one spatially continuous dataset of the entire region. Glacier outlines were obtained from the Randolph Glacier Inventory 5.0 (available from GLIMS at http://www.glims.org/maps/glims) and modified manually to reflect the debris-covered area of each glacier. These were then used as glacier / land masks and only ponds located within this mask were included in the study.

2.3 Maximum Likelihood Classification and Manual Editing

A supervised classification technique was used to automatically delineate supraglacial ponds. First, we manually selected training sites that contained the primary land cover classes (e.g. clean ice, water, debris covered ice etc.) from the true-colour Sentinel 2A image. We then performed the Maximum Likelihood Classification (MLC) on the true-colour image, plus bands 5 and 7 (near infrared and thermal wavelengths respectively): both infrared and thermal wavelengths are absorbed by water bodies so their addition aided the classification substantially. Whilst other classifications can be used (e.g. the Hierarchical Knowledge Based Classifier (HKBC) method), previous studies suggest that MLC is the most accurate classification method for delineating water stores on glaciers (Tiwari et al., 2016). This method was repeated for all image dates. The classification results were assessed manually, by comparing automatically detected pond margins to the underlying imagery. We then manually edited any ponds where the classification had failed to accurately detect the pond margins. In total, we identified 6,533 ponds, and then extracted key statistics for analysis, specifically ponded area and number of ponds.

2.4 Controls on Pond Location

We assessed controls on supraglacial pond formation and growth patterns, specifically: glacier surface slope, ice velocities and the presence of ice cliffs. We derived a slope map and glacier elevation profiles from the ASTER

DEM (http://earthexplorer.usgs.gov/) to identify glaciers with particularly low slope gradients and thus potential areas for future pond development. Glacier velocities were derived from repeat-image feature tracking of Landsat images by Dehecq et al. (2015). The data used in this study are derived from average velocities for 2013-2015 and have a 120 m spatial resolution (Dehecq et al., 2015). Each of the study glaciers were divided into 10 bands, representing 10% glacier surface area, to facilitate comparison of pond locations with surface slope and ice velocities.

3. Results

3.1. Supraglacial Pond Change

3.1.1. Regional Ponded Area Change

Across the study region, total ponded area increased on all 10 glaciers between 2015 and 2018 (Fig. 2). The most prominent changes in both pond number and area were observed on the three largest glaciers (SI. Table 2; Ngozumpa, Pangbung and Khumbu glaciers), which contain ~58% of the total 6,533 ponds identified in this study (Fig. 2). Specifically, ponded area increased by 255,849 m^2 (33.3 %) on Ngozumpa Glacier, 191,386 m^2 (36.2 %) on Pangbung Glacier and 134,299 m^2 (43.1 %) on Khumbu Glacier between December 2015 and April 2018 (Fig. 2). This increase mainly resulted from pond coalescence on Ngozumpa and Khumbu glaciers, as the number of ponds decreased but the ponded area increased (Sl. Fig. 1): the number of ponds decreased by 60 (13.5% decrease) on Ngozumpa and 3 (1%) on Khumbu (Fig. 2.). The remaining seven smaller glaciers showed an increase in ponded area between 2015 and 2018, ranging from 9,664 m^2 on Imja Glacier (30 % increase) to 120,162 m^2 on Lhotse Glacier (68 % increase). This increase in area was a result of both the establishment of new ponds and the coalescence of existing smaller area ponds (Fig. 2), for instance ponded area on Ama Dablam Glacier increased 38,958 m^2 and pond number increased by 29.

Whilst total ponded area on all glaciers increased from 2015-2018 (SI. Table 2), the number of ponds found on each glacier varied (Fig. 2). Only 2 of the 10 glaciers showed an increase in pond number: on Pangbung Glacier the number of ponds increased by 4, to a total of 200 ponds, and on Ama Dablam Glacier the number of ponds increased by 29, to a total of 67 ponds (December 2015- April 2018). The remaining 8 glaciers exhibited an overall decrease in the number of ponds, ranging from a reduction of 2 (Lhotse Glacier) to 60 (Ngozumpa Glacier). Glaciers with decreasing pond numbers generally showed an increase in ponded area in 2015, 2017 and 2018 (SI. Fig. 1). The exception to this inverse relationship between pond number and ponded area was in 2016 (SI. Fig. 1). During this year, a large decease in pond number was observed on glaciers in the eastern part of the study area, particularly Lhotse, Lhotse Shar and Lhotse Nup glaicers (Fig. 2b). At the same time, there was a large increase in pond number on glaciers in the western part of the study area (Fig. 2c). For example Pangbung Glacier increased in pond number from 196 (2015) to 468 (2016), and Sumna Glacier increased from 78 (2015) to 182 (2016). Overall, our results show that ponded area increased on all glaciers during the study period 2015-2018, whereas the number of ponds generally declined, despite the considerable spatial variability observed in 2016 (Fig. 2c).

Two water bodies in the study area were assessed separately, due to their large size; supraglacial lake 'Spillway Lake' on the terminus of Ngozumpa Glacier, and proglacial lake 'Imja Lake' fronting the Imja/Lhotse Shar Glacier complex (Fig. 4). Spillway Lake, located at the terminus of Ngozumpa Glacier, underwent a net gain of 40,565 m^2 during the study period (December 2015 - April 2018) and reached a size of 286,367 m^2. This remains the largest surface water store in the study region. The only proglacial lake identified in this study was Imja Lake, which expanded up-glacier by 455.6 m to reach and area of size of 1,493,142.68 m^2 by 2018. Whilst these two water bodies are currently the only very large water bodies in the study area, our data show substantial growth and coalescence of surface ponds on Pangbung and Khumbu glaciers (Fig. 3b, c).

3.1.2 Glacier-scale Pond Changes

Despite the overarching trends across the region, changes in supraglacial pond number and area varied from glacier to glacier and across individual glaciers (Fig. 2; Table 2). For the largest three glaciers, most of the ponded area was located near the terminus, and this persisted throughout the study period (Fig. 3a-c). The number of ponds, although demonstrated an overall decrease, remained relatively similar over the four year period, but ponded area increased (Fig. 2), which was primarily as a result of coalescence on the lower glacier tongues. (Fig. 3a-c). For example, on the terminus of Ngozumpa Glacier, two smaller ponds (Fig. 3a, i and ii) formed new branches of Spillway Lake in March 2017. This reduced the total number of ponds by 2, whilst increasing the total ponded area of Spillway Lake. Similarly, along the eastern margins of Khumbu Glacier, lateral pond expansion between March 2016 and March 2017 (Fig. 3b, i and ii) resulted in coalescence of two major ponds and a reduction in the number of surface ponds by 2. Our data therefore suggests that supraglacial pond expansion on the larger glaciers in our study area results from pre-existing ponds coalescing, rather than by the formation and growth of new ponds.

On the seven smaller glaciers, there was substantial spatial and temporal variability in the number and area of surface ponds, both between the glaciers and across individual glaciers (Fig. 3d and Fig. 4). For example, Lhotse Shar and Imja Glacier neighbour each other, in the east of the study region (Fig. 1). However in April 2018, Lhotse Shar Glacier had over three times the ponded area (135,420 m^2) of Imja Glacier (42,603 m^2) as well as almost three and a half times the number of ponds (96 and 28 respectively). Sumna Glacier in the west of the region showed major variations in ponded area and number over time, as its percentage pond cover ranged from 2.16 % to 4.87 % during the four year study period. For most of the smaller glaciers, ponds occupied similar locations at each time step (e.g. Ama Dablam Glacier SI. Fig. 2a and Lhotse Glacier SI. Fig. 2b), in addition to the growth of new ponds (e.g. Lhotse Glacier SI. Fig. 2b). Sumna Glacier was the exception to this and showed a distinctive change in the spatial pattern of the pond locations during the study period: at the start of the study (2015), it had more ponds at higher elevations, but by the end (2018), ponds were most concentrated near the terminus (Fig. 3d). Overall, our results show an increase in both ponded area and number of ponds on the smaller glaciers, but this showed substantial spatial and temporal variation, even between neighbouring glaciers and on the same glacier.

3.2 Controls on Pond Location

3.2.1 Glacier Elevation Profile

The study glaciers have an average slope > 18° at the tongue and < 25° at higher elevations. In general, areas where the mean overall slope is lower (>10°) contain more ponds Overall, slope angle tends to decrease closer to the glacier termini, where slopes are generally between 2° and 4° (Fig. 5). However, with the exception of Sumna Glacier (see section 3.1.2.) there is no apparent relationship between elevation and pond number/ area on the study glaciers (Figs. 5 and 6). We assessed this in further detail by dividing each glacier into 10 equal elevation bands (to account for differences in total length and to facilitate direct comparison between glaciers) and calculating the number and area of ponds in each elevation band (Figs. 5 and 6). Bands are numbered from 1 (the glacier head wall) to 10 (terminus). On six of the ten study glaciers, the number of ponds decreased from the head of the glacier to terminus, whilst the pattern was reversed on the remaining 4, so that pond numbers increased with distance up glacier (Fig. 5 and 6). Furthermore, all the study glaciers showed large variations in ponded area and number between individual elevation bands. For all study glaciers, the largest number of ponds were usually found in the central elevation bands (bands 5-6), as exemplified by Pangbung (32.2 % of ponds), Khumbu (23.1 %) and Lhotse Shar (47.8 %) glaciers (Fig. 5). The exception to this trend can be seen on Imja, Lhotse and Sumna glaciers, where the highest numbers of ponds can be found nearer to the terminus (i.e. elevation bands 9 and 10), and Ama Dablam Glacier where most ponds are located nearer the high accumulation zone (bands 1-2; Fig. 5). Furthermore, the number of ponds was much higher on Imja Glacier's terminus (band 10; 6 ponds; 21.4 %) than on any of the other study glaciers. No ponds where identified in the high accumulation zone (band 1) for four of the ten study glaciers; Imja, Nuptse, Lhotse Shar and Sumna (Fig. 5 and 6). Sumna Glacier also displayed distinctive areas of higher frequency ponding (bands 6-8) and lower frequency ponding (bands 2-4) which showed no clear relationship with elevation (Fig. 3d; Fig. 5). A number of breaks in slope were identified on six of the ten study glaciers: Ama Dablam, Imja, Lhotse, Lhotse Shar, Lhotse Nup and Sumna (Fig. 5). In the band immediately down glacier of the break in slope, there was an increase in pond number on four of the glaciers (Imja, Lhotse, Lhotse Shar, and Sumna; Fig. 5). This was most notable on Lhotse Glacier, where there was a change in slope in band 1 and the number of ponds increased from 1 (band 1) to 20 (Band 2) (Fig. 5). Ama Dablam and Lhotse Nup were the exception to this trend, where on Ama Dablam Glacier there was a decrease in pond number from 8 to 4, following the break in slope in band 3 (Fig. 5) whilst on Lhotse Nup a break in slope in band 6 preceded a decrease in pond number from 7 to 1 (Fig. 5).

3.2.2. Glacier Velocity

Generally, glacier velocity decreased from source to terminus, being highest in bands 1-3 and lowest in the bands 8-10 (Fig. 7). Where velocities were higher, the number of surface ponds was generally lower (Fig. 7). For instance, in bands 1 and 2 on Lhotse Shar Glacier there were no ponds recorded (velocity >20 ma^{-1}). However, further down glacier from band 3, velocities were lower (<20 m a^{-1}) and the number of ponds increased by 14 (14.6 %) (Fig. 7). The main exception to this trend is Nuptse Glacier, where velocity is low in bands 1-2 (> 2 ma^{-1}) and there are no ponds, but the area of higher velocity in bands 4 to 5 (>14 ma^{-1}) contains a total of 34 ponds (Fig. 7). In general, where velocities are lowest, for instance nearer the glacier terminus, pond number increases, following a similar trend to that of glacier slope (section 3.2.1.). For example, from band 5 onwards on Lhotse Shar Glacier, there is almost no recordable velocity and pond number reaches its highest (23 ponds) (Fig. 7). The relationship between total pond area and glacier velocity is similar to that for pond number (Fig. 8): higher velocities coincide with lower ponded area, whereas lower velocities have a higher ponded area (Fig. 8). Sumna Glacier displays this relationship clearly: it has 23 % of its ponds in Bands 2-4 and 70 % in bands 6-8. This corresponds to velocities of 3 to 7 ma^{-1} and < 3 ma^{-1} respectively. Overall, our results indicate that lower velocities correspond with higher ponded area and pond number, and higher velocities generally relate to fewer ponds.

3.2.3. Ice Cliffs

Although ice cliffs were identified on all 10 glaciers 2015-2018, the number of cliffs changed markedly during this period, with cliffs seen to increase and decrease from year to year, and between glaciers (Fig. 9). Ngozumpa and Khumbu glaciers had the highest percentage area of the glacier covered by ice cliffs, with 4.3% and 3.92% respectively, and Sumna glacier the least (1.1%; Fig. 9). The greatest temporal variability was observed on Ama Dablam Glacier, where ice-cliff coverage decreased from 2.59 % in 2015 to 1.3 % in 2016, and then rapidly increased to 3.3 % in 2018 (Fig. 9). The number of supraglacial ponds with a corresponding ice-cliff exceeded the number without: on average, across all of the study glaciers, 54 % of ponds had a coincident ice-cliff (Fig. 9). During the study, the number of ponds without an ice cliff increased on average by 1.6 % of the total glacier surface area and this was most noticeable on the seven smaller glaciers (Fig. 9). For instance, on Sumna Glacier, the area of the ponds with a cliff remained relatively stable (~ 0.8 %), whereas the area of ponds without a cliff increased from 1 % in 2015 to 1.75 % in 2018 (Fig. 9). In comparison, the number of ponds with an ice cliff increased by just 0.9 %, observed most notably on the three larger glaciers (Fig. 9). For example, on Ngozumpa Glacier, ponds with cliffs average 4.3 % compared to just 1.25 % for ponds without cliffs. This indicates pond growth can occur irrespective of ice cliff presence. 2018 saw a marked increase in ponded area without an adjacent ice cliff, increased on average by 1.4 % (average of 9 glaciers) with the exception of Sumna Glacier where there was a decrease (0.32 %).

3.3 Future Lake Development

Each of the 10 study glaciers was assigned a number, according to the stage of lake development described in established lake classification schemes (Komori, 2008; Robertson, 2012; Table 3). In 2015 (Fig. 10b), the study region was dominated by glaciers in Stage 2 of lake development, with 60% showing ponds that have coalesced, were ice-dammed and have large areas (>20,000m^2). Only Ngozumpa Glacier was defined as Stage 3, due to the presence of the large terminal Spillway Lake (Fig. 10). The remaining three glaciers (Sumna, Lhotse Nup and Ama Dablam Glaciers) were all classified as Stage 1, with supraglacial ponds forming in their lower ablation zones (Fig. 10b).

Over the four-year study period, (December 2015- April 2018) two glaciers (Ama Dablam and Lhotse Nup) transitioned to a new stage of lake development (Fig. 10). Both progressed from Stage 1, where a few supraglacial ponds were identified, to Stage 2, where ponds had begun to coalesce (Fig. 10). Two glaciers (Pangbung and Lhotse Shar) partially transitioned from Stage 1 to Stage 2, and from Stage 2 to Stage 3, respectively (Fig. 10). Features that fit more than one stage were identified on these two glaciers, meaning that they could not be assigned a stage using the current classification. For example, on Pangbung Glacier, ponds were appearing on the lower ablation zone (characteristic of Stage 1), but some ponds were also beginning to coalesce (Stage 2; Fig. 3c). On Lhotse Shar Glacier, coalescing was observed (Stage 2), but there was also stable expansion of its proglacial lake (Stage 3). As a result, the current development cannot be captured by existing schemes.

4. Discussion

4.1. Changes in Supraglacial Pond Area 2015-2018

The area of supraglacial ponds in the study increased markedly between 2015 and 2018, ranging from a 13.6 % increase on Sumna Glacier to a 108.1 % increase on Lhotse Nup Glacier, despite showing large inter-annual variations (Fig. 2). These increases show a marked acceleration in pond growth, compared to 2000-2015 (Watson et al., 2016). For instance, ponded area increased at a rate of 1.6 % a^{-1} on Nuptse Glacier between 2000 and 2015 (Watson et al., 2016), whereas our study measured a rate of 22.6 % a^{-1} between 2015 and 2018 (SI. Table 2). Similarly, the rate of expansion on Lhotse Glacier in our study (17.0 % a^{-1}) is four times greater than that found by Watson et al. (2016; 4.1 % a^{-1}). This is a major concern in terms of risks to downstream communities, as these very high rates of pond growth will rapidly increase the water volumes available for outburst floods and will also encourage pond coalescence and lake formation.

One potential explanation for the observed acceleration in pond growth is climatic controls: warmer temperatures should increase melt rates and hence encourage pond expansion, whilst increased precipitation could add water directly to the ponds. Data on climate trends proximal to our study glaciers are very limited. However, available data (Salerno et al., 2015) suggest that minimum and mean air temperatures have risen in the Everest area between 1994 and 2013, at elevations above 5000 m. However, warming was most marked in spring and winter, and would thus have a more limited impact on ice melt, and it was concurrent with a reduction precipitation, which would decrease direct inputs to the ponds (Salerno et al., 2015). As such, we suggest that the observed increase in ponding may at least partly reflect changes in the dynamics of our study glaciers, which provide the conditions that promote pond formation. Between 2000 and 2017, glaciers in East Nepal decelerated by -1.8 ± 0.1 ma^{-1} (17.0 ± 1% a^{-1}) and thinned, which in turn reduced driving stresses (Dehecq et al., 2018). Down-wasting and deceleration creates an inverted mass balance gradient and an uneven glacier surface, which together facilitate pond formation (Reynolds, 2000; Miles et al., 2016 and 2017). Furthermore, slow flow is likely to reduce the number of crevasses forming and would thus reduce the chance of pond drainage (Immerzeel et al., 2014; Miles et al., 2017; Watson et al., 2017a and 2017b). As such, we suggest that recent changes in ice dynamics in the Everest region are likely to be contributing to observed pond growth and that this may lead to a positive feedback, whereby rapid pond growth accelerates down wasting, leading to further pond expansion.

4.2. Glacier-scale Ponded Area Patterns

The three larger glaciers (Ngozumpa, Khumbu and Pangbung) increased in ponded area between 2015 and 2018, but decreased in pond number (Fig. 2). This suggests that pond area is increasing via coalescence, as seen at the terminus of Ngozumpa Glacier (Fig. 3a) and the eastern margins of Khumbu Glacier (Fig. 3b). This has implications for both glacier lake related hazards and ice loss rates in the future. As ponds continue to join, and the area of supraglacial ponds increases, the likelihood of proglacial lakes formation is increased (Komori, 2008; Robertson, 2012), which in turn increases the risk of GLOFs (e.g. Richardson, 2000; Quincey et al., 2007; Benn et al., 2012; Rounce et al., 2017). In addition, the larger ponded surface area increases the wind fetch, which may lead to enhanced undercutting at pond margins and thus increase glacier melt rate (Benn et al., 2001; Röhl, 2006, 2008; Sakai et al., 2009). Our data demonstrate that the three largest glaciers had low velocities across their tongues: on Ngouzmpa and Pangbung glaciers, velocity remained below 12 ma^{-1} for all 10 bands, whilst on Khumbu Glacier velocities started high (> 30 ma^{-1}) in band 1, but rapidly reduced to below 12 ma^{-1} for the remaining 9 bands (Fig. 7 and 8). We suggest that these slow velocities promoted pond coalescence and growth (Benn et al., 2012, 2017) and also reduced the frequency of pond drainage, by limiting the number of open crevasses (e.g. Miles et al., 2017), and thus increasing pond area.

Generally, the smaller glaciers in the region do not have large, extensive ponding at their termini, but the ponded area on all seven of the smaller glaciers increased during the study period (Fig. 2). For example, the ponded area and pond number found on Ama Dablam Glacier increased by 38,958 m^2 (48 %) and 29 (43 %) respectively 2015 to 2018 (Fig. 2b, c). Given the increase in area of the ponds but variations in pond number, we suggest that this is primarily due to the coalescing of smaller area ponds (e.g. Ama Dablam Glacier SI. Fig. 3) but also through the formation of new ponds, which is consistent with earlier observations (Watson et al., 2016). This may enhance melt rates, by increasing the fetch across the pond and increasing the ponded area (Sakai et al., 2009), and potentially lead to proglacial lake development. Ice velocities are generally higher on the smaller glaciers, and more spatially variable, which may limit the opportunity for pond growth and/or encourage crevasses formation and thus promote drainage (e.g. Immerzeel et al., 2014; Miles et al., 2017; Watson et al., 2017a).

4.3. Evaluating the use of Sentinel Data for Remote Sensing Studies

Previous studies of supraglacial and proglacial lakes changes in the Everest region have largely used Landsat imagery (30 m, 1 pixel = 900 m^2) (Table 1; e.g. Gardelle et al., 2011; Nie et al., 2013; Zhang et al., 2015). Here we use Sentinel 2, which is 10 m resolution (1 pixel = 100 m^2). Our results demonstrate that ponds < 100 m^2 (one pixel in Sentinel data) accounted for 3% - 8% and those < 400 m^2 (four pixels in Sentinel data) comprised 28% - 59% of total ponds found in the region (SI. Fig. 4). Of the total ponds identified, between 55 % and 86 % were below 900 m^2 (one pixel in Landsat data). As such, using Landsat imagery to map pond changes in the region would have missed the majority of the total number of ponds. Whilst these ponds are comparatively small in area, including them in assessments is vital, as they inform us about where ponds are nucleating, and hence controls on their formation. These data also indicate locations that may become ponded in the future, and therefore subject to enhanced melt rates, and/or areas that may eventually coalesce with other ponded sections. Furthermore, recent work has demonstrated that Sentinel-2 imagery has a better spectral contrast between debris-cover ice and supraglacial ponds than Landsat of RapidEye, which affirms its suitability (Watson et al., 2018).

4.4 Controls on Pond Formation

4.4.1. *Glacier Elevation Profile*

Previous work suggests that supraglacial ponds typically begin to form on slopes < 10 ° and larger ponds occur where surface gradients are less than 2°, typically found close to the glacier terminus (e.g. Quincey et al., 2007; Bolch et al., 2012). In some areas, large number of ponds coincided with slopes of 2-4° and pond frequency was highest at the termini of Imja, Lhotse and Sumna glaciers (Figs. 5 and 6). However, contrary to theory, supraglacial ponds were also found in areas with much greater slope gradients (> 10°), both at the termini and further up-glacier (Figs. 5 and 6). For instance, the highest number of ponds on Ama Dablam Glacier (76 %) were located in the high accumulation zone (band 1-2). We also observed changes in the number of ponds after beaks in slope (Fig. 5), which may reflect localised areas of extensional / compressional flow that would open or close crevasses, and thus facilitate or reduce pond drainage (Benn et al., 2001, 2012; Gulley and Benn, 2007; Röhl, 2008; Thompson et al., 2012; Mertes et al., 2017).

Our data show that the greatest number and area of ponds occur in the mid-elevation bands (bands 5-6) and not at the termini (bands 8-10) of our study glaciers (Figs. 5-6). We suggest this is because of the inverted mass balance gradient observed on debris-covered glaciers in the Everest region: thick debris at the terminus supresses melt, whereas thinner debris further up glacier enhances melt (Bolch et al., 2008; Quincey et al., 2009; King et al., 2018) This pattern of mass balance results in near-stagnant ice velocities over much of the tongue and rapid down-wasting at mid-elevations (Quincey et al., 2007, 2009; Nicholson and Benn, 2013; Juen et al., 2014; King et al., 2017), which produces uneven 'ablation topography' (Nicholson and Benn, 2013). Together, this creates ideal conditions for pond formation. Our data suggest that these conditions are now predominantly found at mid-elevations (bands 5 to 6) on glaciers in the Everest region, and that the area where ponds are able to form may be advancing up-glacier. This has important implications for total ice loss rates, as ponds strongly enhance glacier melting (Sakai et al., 2000; Benn et al., 2001; Miles et al., 2016; Watson et al., 2016; Mertes et al., 2017), and could thus expand the area of enhanced ice loss further up glacier.

4.4.2. Velocity

Ice velocities strongly influence pond size, pond drainage and pond persistence (Miles et al., 2017). Where velocities are low, little reorganisation of internal water pathways can occur, resulting in ineffective englacial drainage from the glacier surface, thus promoting surface ponding (Jordan and Stark, 2001; Benn et al., 2012, 2017). As a result, low surface gradients at glacier tongues generally encourage pond formation and low surface velocities facilitate storage, as opposed to drainage (Reynolds, 2000; Quincey et al., 2007; Watson et al., 2017a). Our results generally support this, as there were more ponds and a greater ponded area closer to the terminus (bands 8-10), where velocities were lower (Figs. 7 and 8) For example, on Sumna, Imja and Lhoste Shar glaciers no ponds were found in bands 1 or 2 where velocity was > 20 ma^{-1}, but as velocity decreased (< 20 ma^{-1}) pond numbers began to increase (Fig. 7). However, as with glacier slope, there are exceptions to this relationship. For example, the peak number of ponds corresponds with peak velocities on Lhotse and near-peak velocities on Nupste (Fig. 7). The cause of these velocity patterns is difficult to elucidate, but we suggest that it may relate to the pattern of debris inputs from the surrounding hillslopes (and hence the debris characteristics and distribution), the location of tributary glaciers and/or meltwater inputs from the surrounding slopes. Overall our data indicate that ice velocities influence pond area and number, but that the relationship is far for simple and requires further detailed study.

4.4.3. Ice-Cliffs

All ten of the glaciers included in this study had surface ice-cliffs, and the majority of ponds were associated with adjacent ice cliffs (54 %). This follows theory, as ice cliffs experience enhanced melt at a rate three to six times greater than that of debris-covered ice (Kirkbride, 1993; Benn et al., 2001; Röhl, 2008; Watson et al., 2016). Thus, ice cliffs can not only initiate pond formation through surface melt (Sakai et al., 2002; Buri et al., 2016a; Watson et al., 2017b) but also facilitate pond expansion in process of thermo-erosional notching (Josberger, 1978; Röhl, 2006). Despite this, our results show that the proportion of ponds without an ice cliff increased substantially during the study period (2015-2018; Fig. 9). For example on Sumna Glacier, ponded area without an adjacent cliff almost doubled during the study, whereas ponded area with a cliff actually decreased, meaning that there were fewer ponds with an ice cliff than without in 2018 (Fig. 9). On Ngozumpa, in contrast, the percentage of ponds with cliffs were on average three times higher (4.3 %) than those without (1.25 %). Overall, our results show that ponds are expanding and that they are usually associated with ice cliffs (Figs. 2 and 9). However, as ponded area increases, the proportion of the ponds with ice cliffs reduces (Fig. 9). We speculate that this may be because pond growth is outstripping ice cliff formation, but this requires further investigation.

4.5. Future Lake Development

4.5.1 Applicability of Lake Classification Models

During this study, two of the ten study glaciers progressed to a new stage of the Komori/Robertson (2008; 2012) proglacial lake classification scheme; Ama Dablam and Lhotse Nup, both progressed from Stage 1 to Stage 2. However, Komori (2008) found glaciers in Bhutan took on average 40 years to pass through Stage 1 and 2, and enter into Stage 3, whilst those the in Aoraki/Mt Cook region took 8-30 years for the same transition (Robertson, 2012). Given the short time-frame of this study (4 years), our results demonstrate that proglacial lakes in the Everest region are evolving rapidly and quicker than other regions, both in the Himalaya and globally. This has important implications for hazard assessments in the region, as these rapid changes require high temporal resolution monitoring to determine potential changes in GLOF risk and could result in hazardous lakes forming quickly in new locations. Our results therefore highlight the need for frequent monitoring of the hazards posed by glacier lake growth in the Everest region, particularly given that Nepal (along with Bhutan) is at the greatest economic risk from GLOFs (Carrivick and Tweed, 2016).

Two of our study glaciers exhibited characteristics of multiple classes of proglacial lake development (Fig. 10). Specifically, on Pangbung Glacier, ponds were appearing on the lower ablation zone, which is indicative of Stage 1 but some ponds were beginning to coalesce (Stage 2) (Table 3). On Lhotse Shar Glacier, we observed coalescing (Stage 2), but also the stable expansion of the proglacial lake (Stage 3). As such, the proglacial lake development observed in our study region does not fit within the four stage classification system of Komori (2008) and Robertson (2012; Table 3). Additionally, changes in ponded area, number of ponds and ice-cliffs were observed on all glaciers (Figs. 2 and 9), but these substantial differences were not accounted for in the current model. For example, both Khumbu and Nuptse glaciers remained in Stage 2 throughout the study period, but experienced increases in ice-cliffs (45 % and 76 % respectively; Fig. 9). Ngozumpa Glacier remained in Stage 3, but showed a marked increase in both ponded area (33 %) and the number of ponds with ice-cliffs (24 %) (Fig. 2c and Fig. 9). As such, the current classification model does not account for many of the observed changes in pond area and characteristics, which could contribute to proglacial lake growth, and does not account for glaciers that bridge different categories. Thus, on the basis of our observations, we propose a six-stage categorisation which accounts for the 'in-stage' changes observed, such as appearance of ice-cliffs and marginal pond expansion (Fig. 11). The inclusion of two additional stages (shown in red), now include 'in-stage' changes observed in this study, such as marginal expansion, ice-cliff formation and pond drainage. The inclusion of these stages would enable us to assign our study glaciers to just one stage, making the model more suitable for evaluating and communicating glacier lake hazard potential.

4.4.2 Lake Development Trajectories and Outburst Risk

A key observation of this study was the coalescing of smaller area ponds on the eastern margins of Khumbu Glacier and the Ngozumpa terminus (e.g. Fig. 3a and b, i and ii). Despite this, both glaciers remained in the same stage of proglacial lake classification during the period (Stage 3 and Stage 2 respectively). Using our new classification scheme, Khumbu Glacier would be classified as Stage 3 (compared to currently assigned Stage 2), suggesting that Khumbu Glacier is further along the progression of proglacial lake formation than previous classifications have indicated. Our data show that Spillway Lake grew by 40,565 m^2 between 2015 and 2018. Previous work showed that Spillway Lake grew by ~ 10% per year (2001 to 2010) to reach 258,000 m^2 in December 2009 (Thompson et al., 2012) but more recently shrank by 8,345 m^2 between 2009 and 2015 (Watson et al., 2016). It was suggested that the reduction in area resulted from supraglacial drainage channel evolution and lowering of the hydrological base level, which paused the lake's expansion (Watson et al., 2016). Given Spillway lake grew by 40,565 m^2 to a size of 286,367 m^2 (December 2015- April 2018), our results indicate the channel has since stabilised, allowing Spillway Lake to expand up-glacier.

During the 4 years of our study, Imja Lake expanded by 456 m up-glacier and Spillway Lake increased in area by ~ 14% a^{-1}. At the same time, we saw large ponds form via coalescing on the margins of Khumbu and Ngozumpa glaciers, and coalescence begin on Ama Dablam Glacier (Fig. 3 and SI. Fig. 2a). We also observed an increase ponded area increased on all of our study glaciers (Fig. 2). As such, our results show that increasing volumes of water are being stored on, and in front of glaciers in the Everest region, and comparison to previous work (Watson et al., 2016) suggests that trend is accelerating. The glaciers in our study region appear to be rapidly moving along the trajectory of proglacial lake formation, and may be doing so quicker than other regions (Komori, 2008; Robertson, 2012). These developments have major implications for downstream GLOF risk, as lake volume and speed of expansion are key factors in the hazard potential of proglacial lakes (Rounce et al., 2017b). As such, there is an urgent need for high resolution monitoring of ice-surface water volumes and proglacial lake development in the Everest Region.

5. Conclusions

This study represents the most up-to-date assessment of supraglacial ponds in the Everest region of Nepal. All 10 glaciers demonstrated an overall ponded area increase over the period 2015 to 2018, ranging from 13.6 % to 108 %. Given the short time span of this study, this is a marked acceleration in the rate of pond growth compared to that of 2000 – 2015 (Watson et al., 2016). This is a major concern for proglacial lake formation and thus future risk to downstream communities. A shift towards pond coalescing was observed, most notably on the three larger glaciers (Ngozumpa, Khumbu and Pangbung). This suggests a transition towards larger surface ponds and lakes. Despite this, smaller area ponds (< 900 m^2) continue to form (accounting for between 55 % and 86 % of the ponds identified in this study) highlighting the need for higher resolution imagery for future remote sensing studies. Our data show the conditions for pond formations are now predominantly found at mid-elevations on glaciers in the Everest region, and the area where ponds can form may be advancing up-glacier. This has important implications for future ice loss in the region. Velocity has been shown to influence both ponded area and pond number, however this relationship requires further study. Ice cliffs were found on all 10 study glaciers, with the highest proportion found on the three larger glaciers, however the rate of formation appears lower than the rate of pond formation in this region. Two glaciers (Ama Dablam and Lhotse Nup) progressed to a new stage of proglacial lake development during the four year study period. This transition is markedly faster than observations elsewhere (e.g. Komori, 2008; Robertson, 2012), and suggests proglacial lakes are evolving much quicker here than other regions, and as such the situation requires continued high temporal resolution monitoring. Given this, our results show existing classification schemes are too simplistic to suitably evaluate and communicate glacier lake hazards, leading to the proposal of a new, six-stage model more suited to evaluating and communicating GLOF hazards.

6. Conflict of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

7. Acknowledgements

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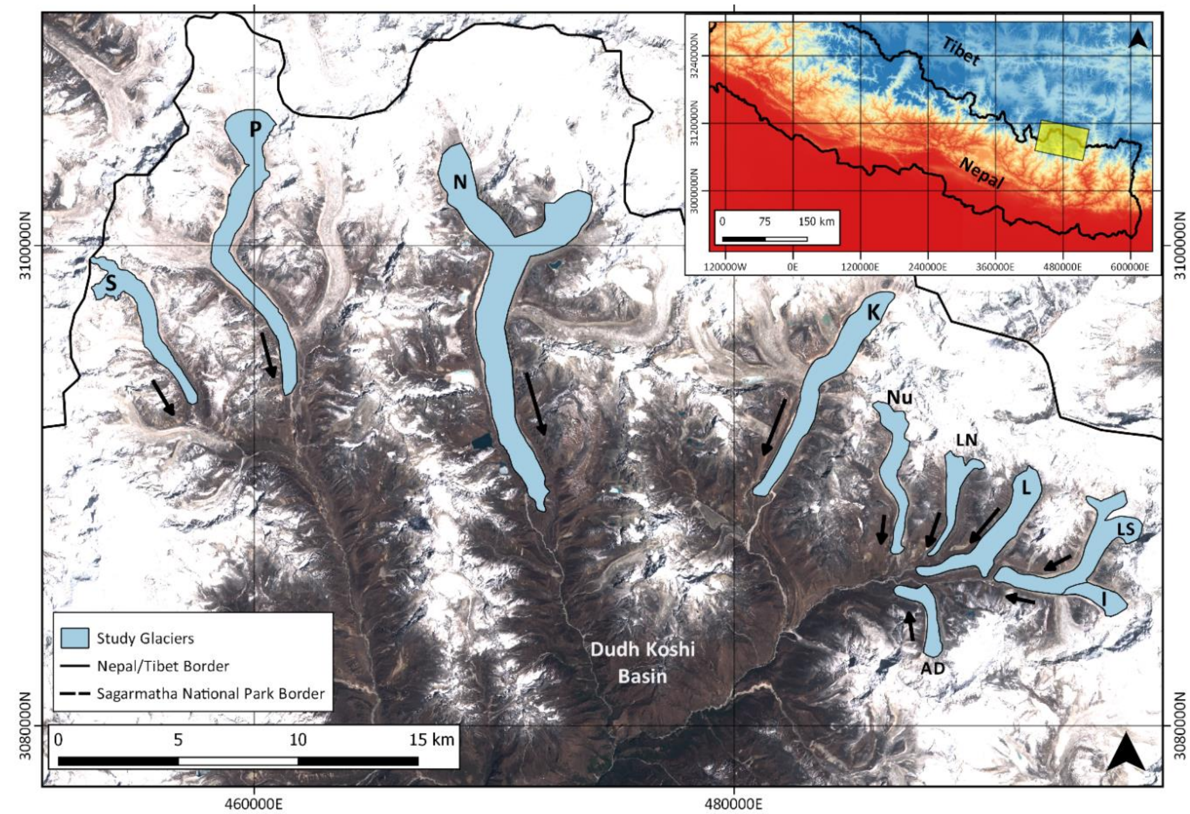

Figure 1: Location of the 10 study glaciers (blue outline) within the Everest region. Arrows dictate direction of ice flow. Glacier names are as follows: S- Sumna Glacier, P- Pangbung Glacier, N- Ngozumpa Glacier, K- Khumbu Glacier, Nu- Nuptse Glacier, LN- Lhotse Nup Glacier, L- Lhotse Glacier, LS- Lhotse Shar Glacier, I- Imja Glacier, AD- Ama Dablam Glacier. Inset: Location of the Everest Region within Nepal. Background image is surface elevation, derived from ASTER DEM (available at http://earthexplorer.usgs.gov/)).

Reference	Date	Imagery	Resolution	Focus
Iwata et al. (2000)	1978-1995	SPOT	Not specified	-Sketch map from SPOT imagery compared to 1987 field survey.
Wessels et al. (2002)	2000	ASTER	15m	-Water delineated for a single time period.
Bolch et al. (2008)	1962-2005	ASTER Landsat	15m 30m	-Normalized Difference Water Index (NDWI) and manual delineation used to classify water bodies.
Gardelle et al. (2011)	1990-2009	Landsat	30m	-Decision tree used to classify lakes using the NDWI.
Salerno et al. (2012)	2008	AVNIR-2	10m	-Manual digitalisation of water bodies.
Thompson et al. (2012)	1984-2010	Aerial Photos ASTER Landsat	<1m 15m 30m	-Multi-temporal analysis of Spillway Lake expansion. Glacier area change not reported.
Nie et al. (2013)	1990-2010	Landsat	30m	-NDWI based classification, but no area changes reported.
Zhang et al. (2015)	1990-2010	Landsat	30m	-Water bodies manually digitalised but ponded area changes not reported.
Mertes et al. (2016)	2014	GeoEye	<1m	-Conceptual model of supraglacial lake evolution based on Ground Penetrating Radar (GPR) facies analysis of Spillway Lake.
Watson et al. (2016)	2000-2015	GoogleEarth WorldView 1&2, GeoEye, QuickBird-2	2m 0.5-0.6m	-Water bodies semi-automatically or manually digitised. Area changes are quantified.

TABLE 1: PREVIOUS REMOTE SENSING STUDIES OF SUPRAGLACIAL WATER STORAGE IN THE EVEREST REGION (AFTER WATSON ET AL., 2016)

Glacier	Area (km^2)	Length (km)	Min-Max Elevation (range) (m)
Ama Dablam	2.13	4.40	4769 – 5084 (315)
Imja	1.08	2.46	5023 – 5187 (164)
Khumbu	6.64	10.82	4956 – 5246 (290)
Lhotse	5.74	6.69	4715 – 5245 (530)
Lhotse Nup	1.38	3.82	4954 – 5310 (356)
Lhotse Shar	3.00	4.03	5008 – 5429 (421)
Ngozumpa	15.10	15.76	4868 – 5541 (673)
Nuptse	3.06	6.20	4662 – 5354 (692)
Pangbung*	11.34	13.14	4742 – 5380 (638)
Sumna*	5.34	7.39	4888 – 5502 (614)

TABLE 2: CHARACTERISTICS OF THE 10 STUDY GLACIERS, SHOWING AREA, LENGTH, ELEVATION AND DIRECTION OF FLOW. *INDICATES GLACIERS NOT INCLUDED IN THE WATSON ET AL. (2016) STUDY.

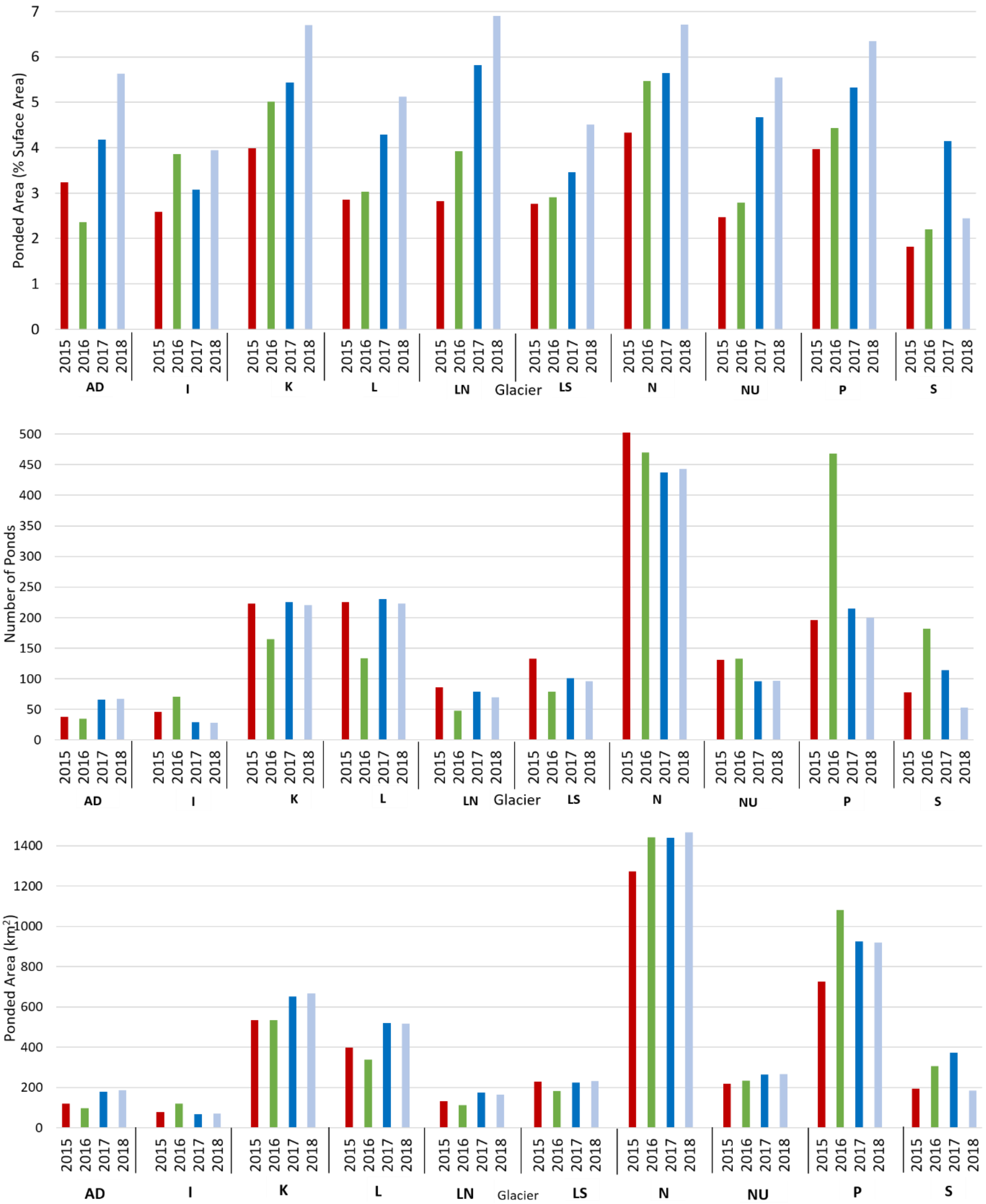

FIGURE 2: CHANGES IN SUPRAGLACIAL PONDS OBSERVED ON ALL 10 GLACIERS MARCH 2015- APRIL 2018; (A) PONDED AREA AS A PERCENTAGE OF TOTAL GLACIER AREA, (B) TOTAL NUMBER OF PONDS AND (C) TOTAL PONDED AREA. BARS ARE COLOUR CODED BY DATE. AD-AMA DABLAM GLACIER, I-IMJA GLACIER, K-KHUMBU GLACIER, N-NGOZUMPA GLACIER, NU-NUPTSE GLACIER, L-LHOTSE GLACIER, LN-LHOTSE NUP GLACIER, LS-LHOTSE SHAR GLACIER, P-PANGBUNG GLACIER, S-SUMNA GLACIER.

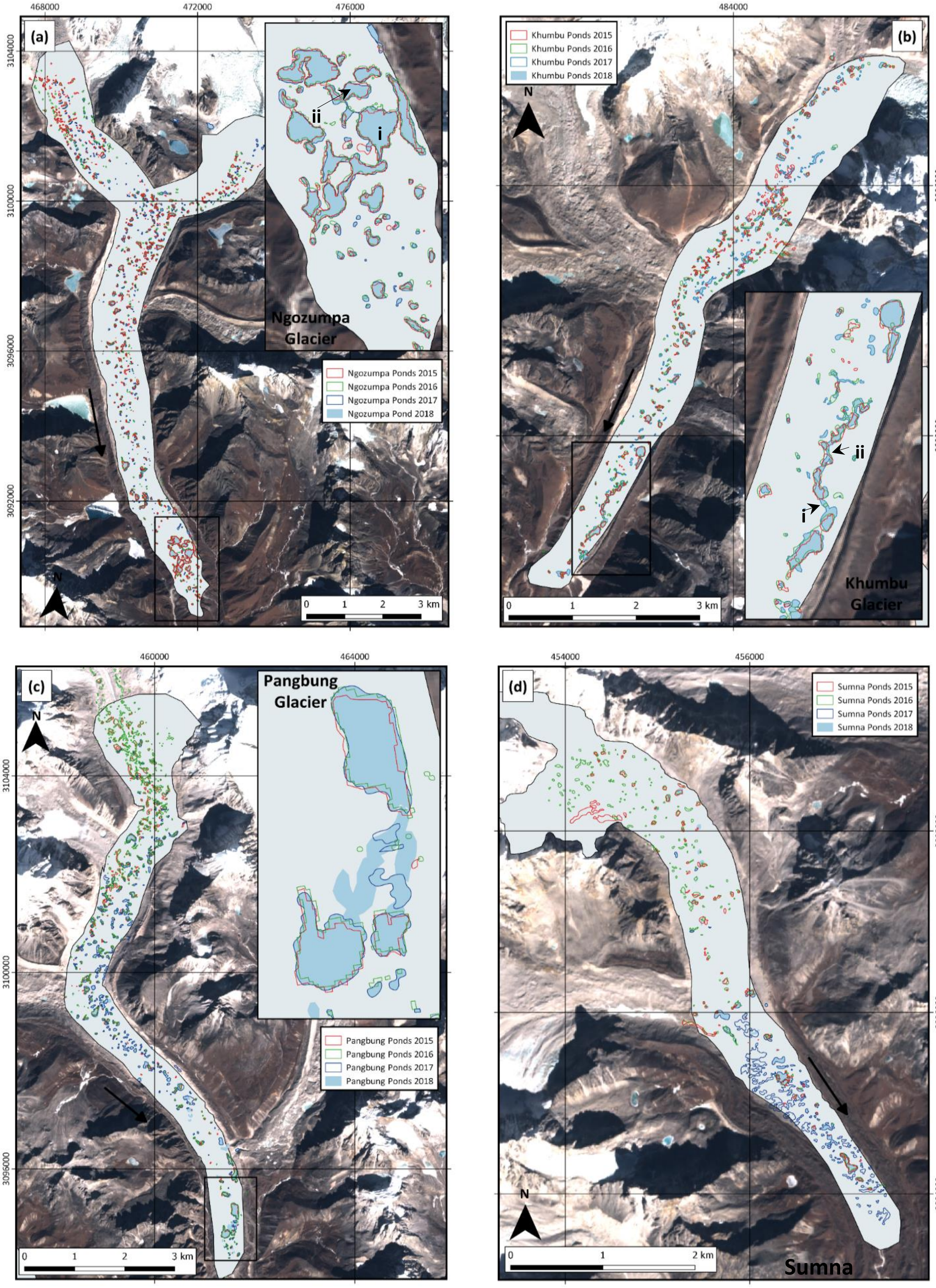

Figure 3: Ponded area change for the Ngozumpa (a) Khumbu (b) Pangbung (c) and Sumna (d) Glaciers, for the period 2015-2018. Inset (a) up-glacier expansion of Spillway Lake, inset (b) pond expansion along the lower eastern margins of Khumbu Glacier, inset (c) pond expansion on the glacier tongue, (d) pond proliferation on the lower ablation zone 2015-2017 and drainage along the western margins 2017-2018. Arrows indicate direction of ice flow. Background image is 2018 Sentinel-2 imagery (from USGS at *http://earthexplorer.usgs.gov/*).

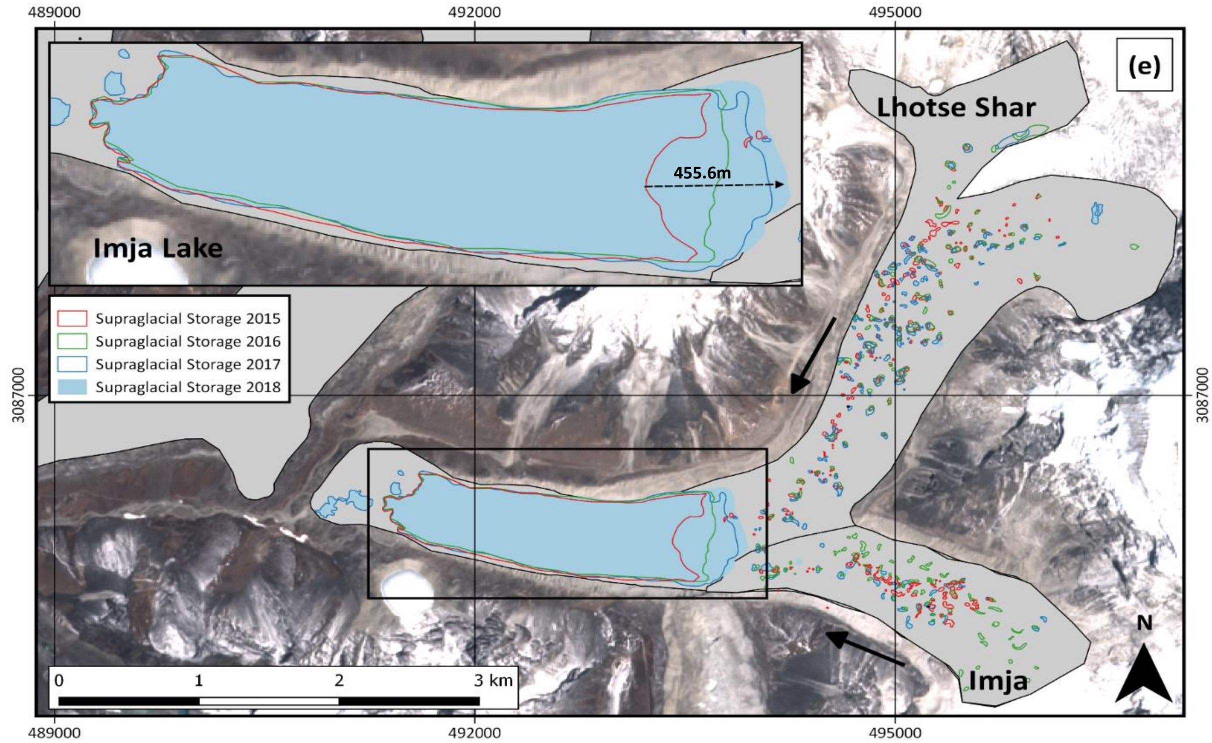

Figure 4: Area change of Imja Lake, in the southeast of the region for the period 2015-2018. Arrows indicate direction of ice flow. Background image is 2018 Sentinel-2 imagery (freely available from USGS at http://earthexplorer.usgs.gov/).

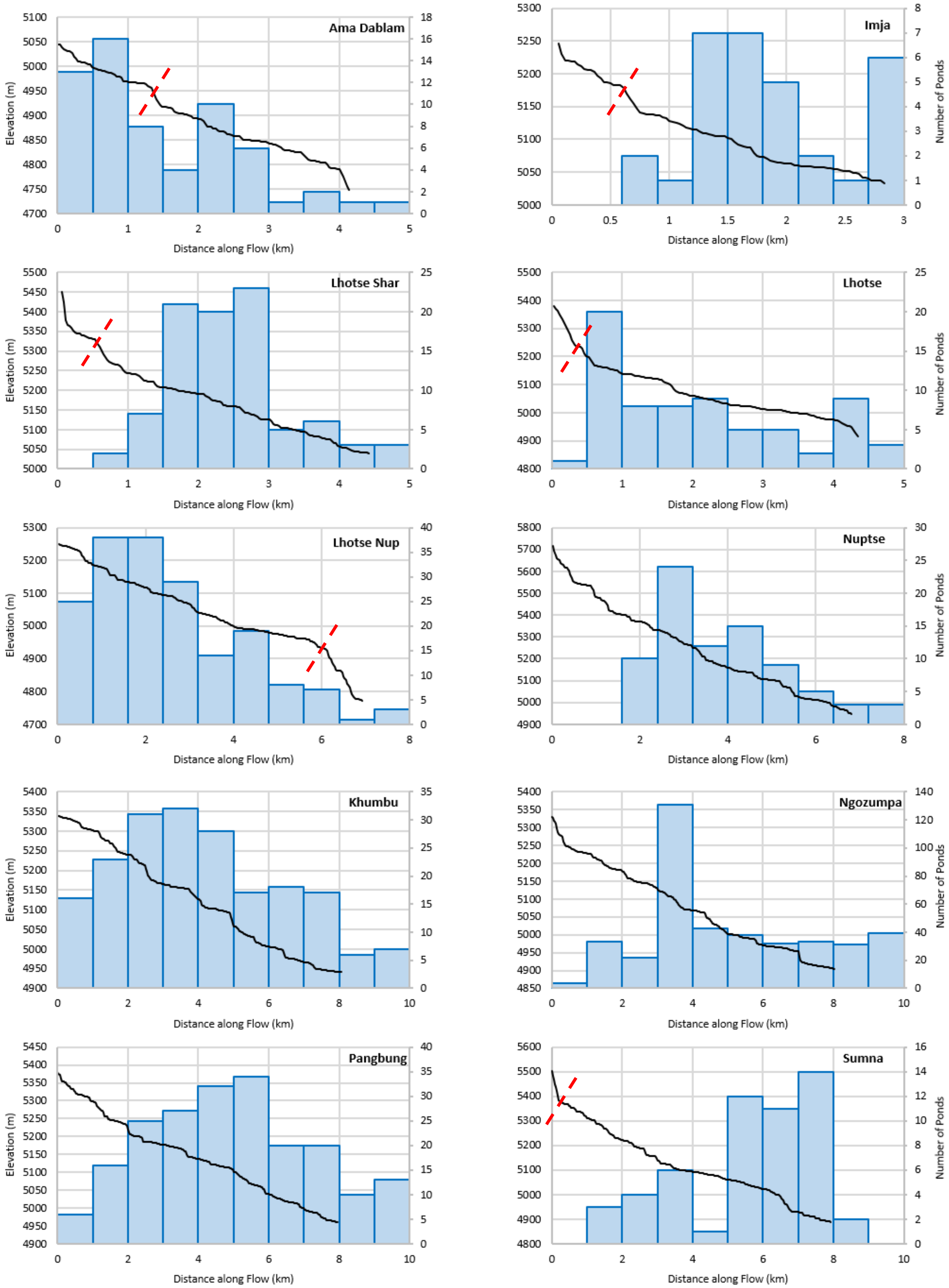

FIGURE 5: NUMBER OF PONDS FOUND ON THE GLACIER SURFACE APRIL 2018 COMPARED TO GLACIER ELEVATION/SLOPE AT 10% GLACIER AREA DISTANCE BANDS (0-10 = BAND 1, 10-20= BAND 2 ETC.) DASHED RED LINE INDICATES BREAKS OF SLOPE.

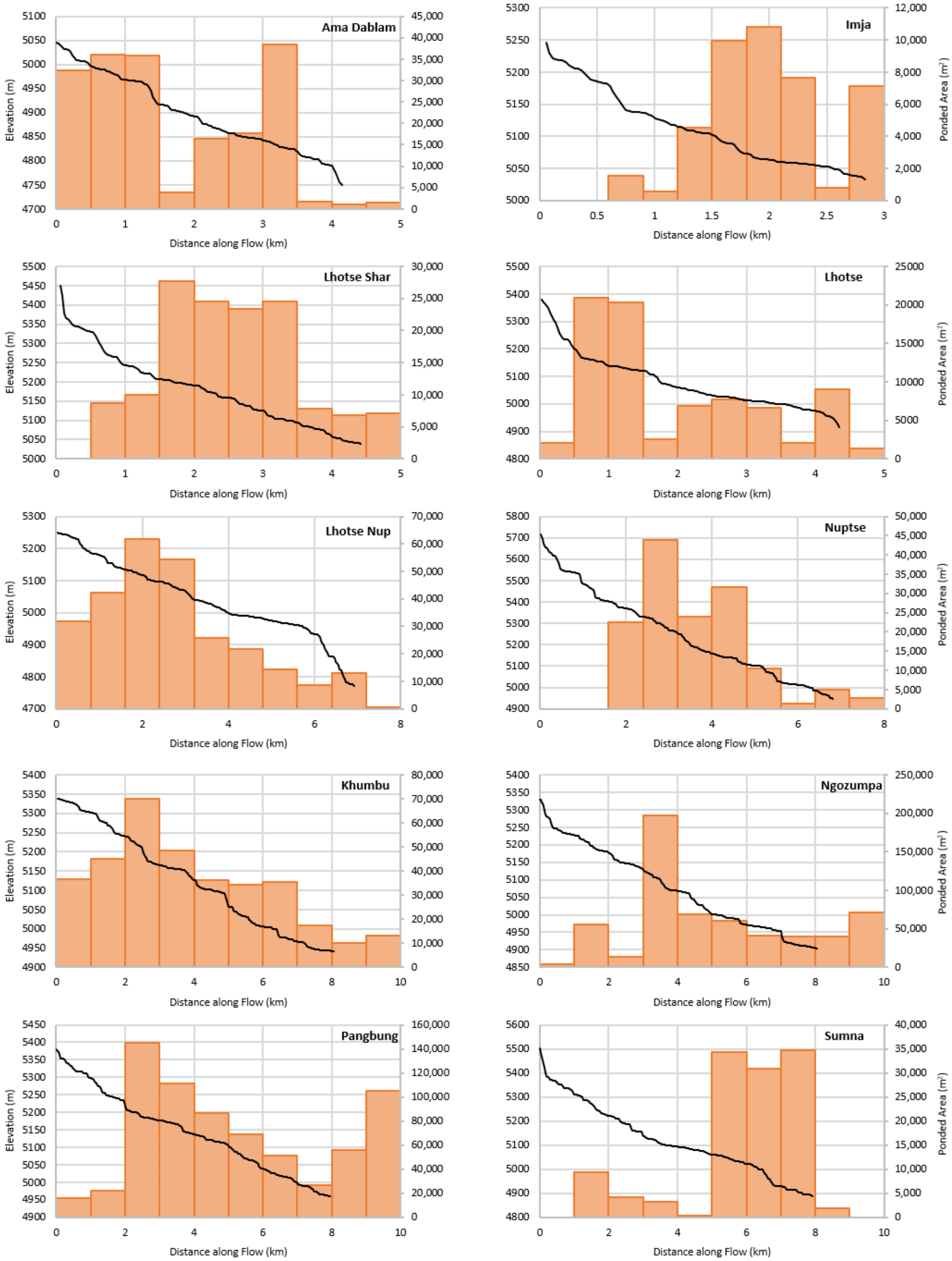

FIGURE 6: PONDED AREA FOUND ON THE GLACIER SURFACE APRIL 2018 COMPARED TO GLACIER ELEVATION/SLOPE AT 10% GLACIER AREA DISTANCE BANDS (0-10 = BAND 1, 10-20= BAND 2 ETC.)

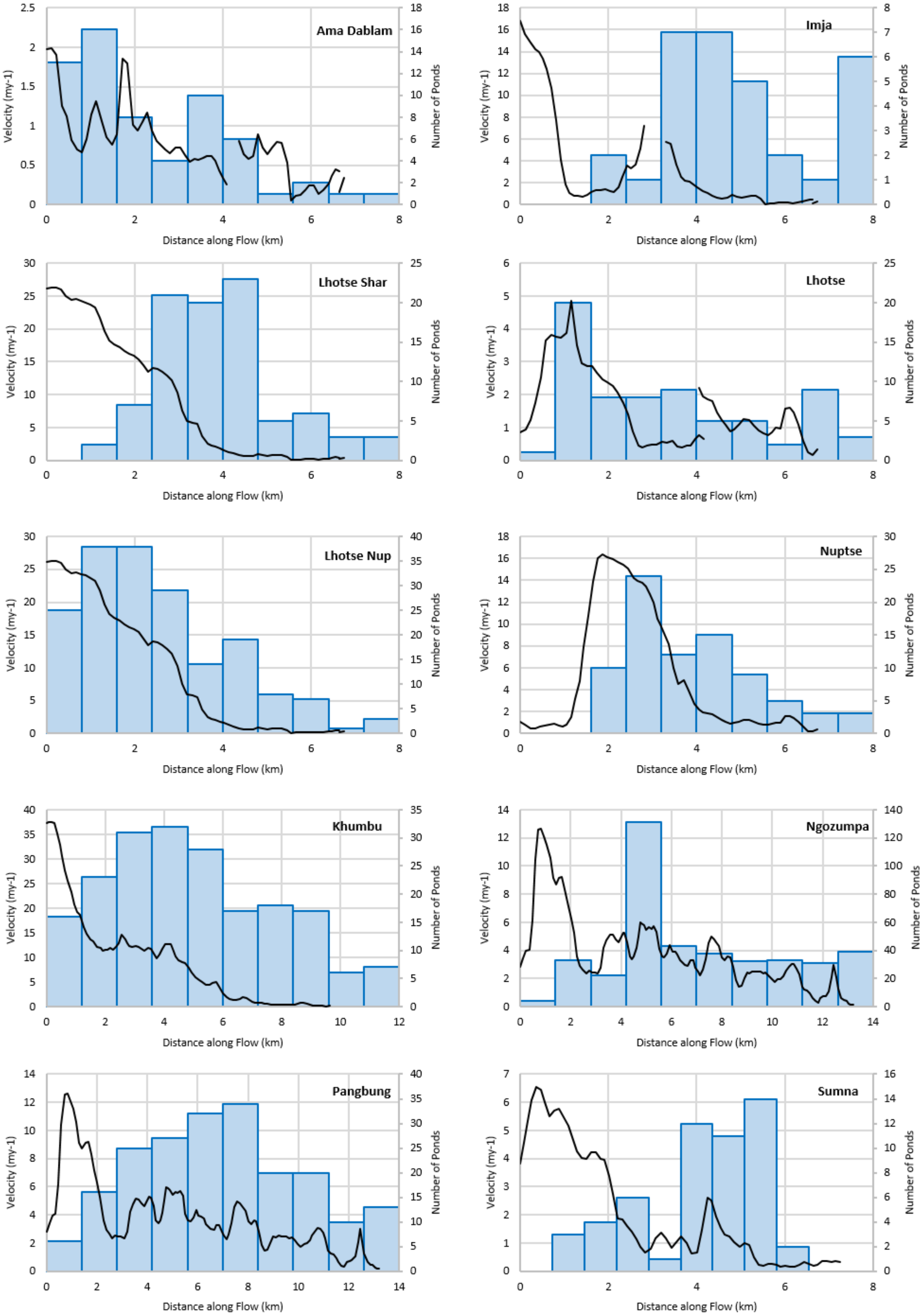

FIGURE 7: NUMBER OF PONDS FOUND ON THE GLACIER SURFACE APRIL 2018 COMPARED TO GLACIER VELOCITY AT 10% GLACIER AREA DISTANCE BANDS (0-10 = BAND 1, 10-20 = BAND 2 ETC.

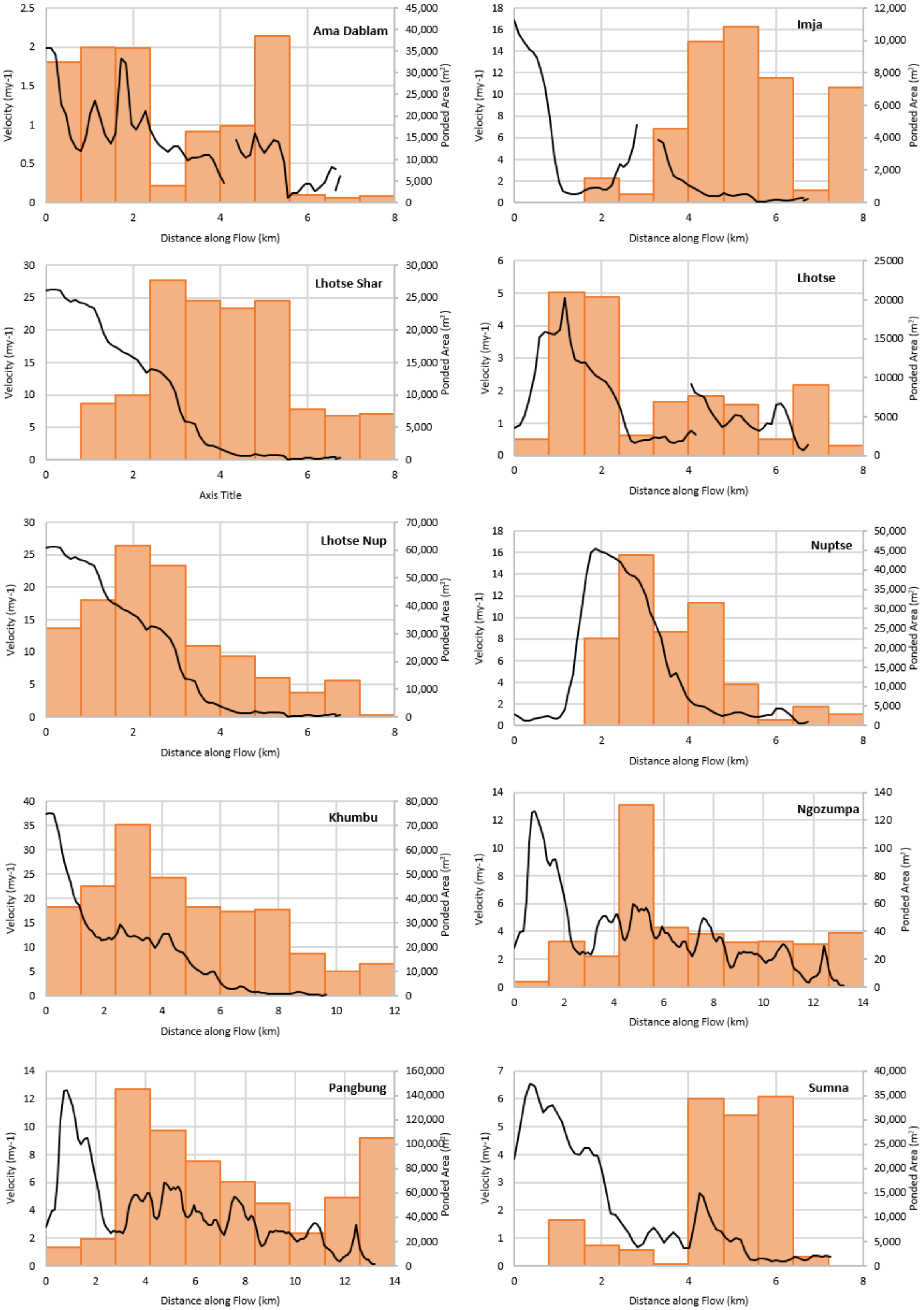

FIGURE 8: PONDED AREA FOUND ON THE GLACIER SURFACE APRIL 2018 COMPARED TO GLACIER VELOCITY AT 10% GLACIER AREA DISTANCE BANDS (0-10 = BAND 1, 10-20 = BAND 2 ETC.)

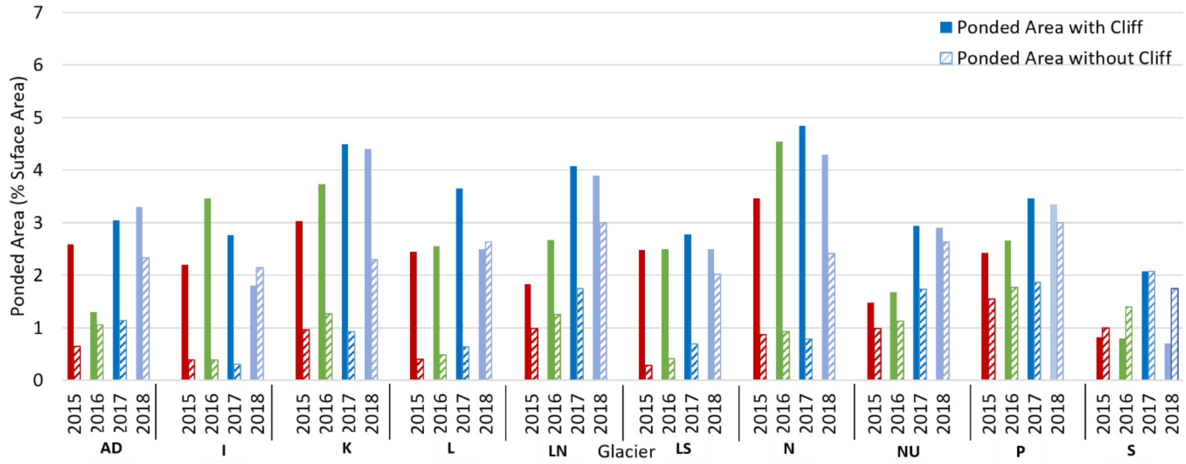

Figure 9: Percentage of ponds with and without ice-cliffs, displayed as percentage of total glacier surface area. AD- Ama Dablam Glacier, I- Imja Glacier, K- Khumbu Glacier, N- Ngozumpa Glacier, NU- Nuptse Glacier, L- Lhotse Glacier, LN- Lhotse Nup Glacier, LS- Lhotse Shar Glacier, P- Pangbung Glacier, S- Sumna Glacier.

Stage of Lake Development	Description
0	No supraglacial ponds.
1	Appearance and growth of supraglacial ponds in the lower ablation zones
2	Coalescing of supraglacial ponds to form larger, ice dammed ponds.
3	Stable expansion of ponds up-glacier and shift to moraine dammed proglacial lake.
4	Glacier retreats out of the proglacial lake.

694 **TABLE 3: STAGE OF LAKE DEVELOPMENT FOLLOWING KOMORI (2008) AND ROBERTSON (2012).**

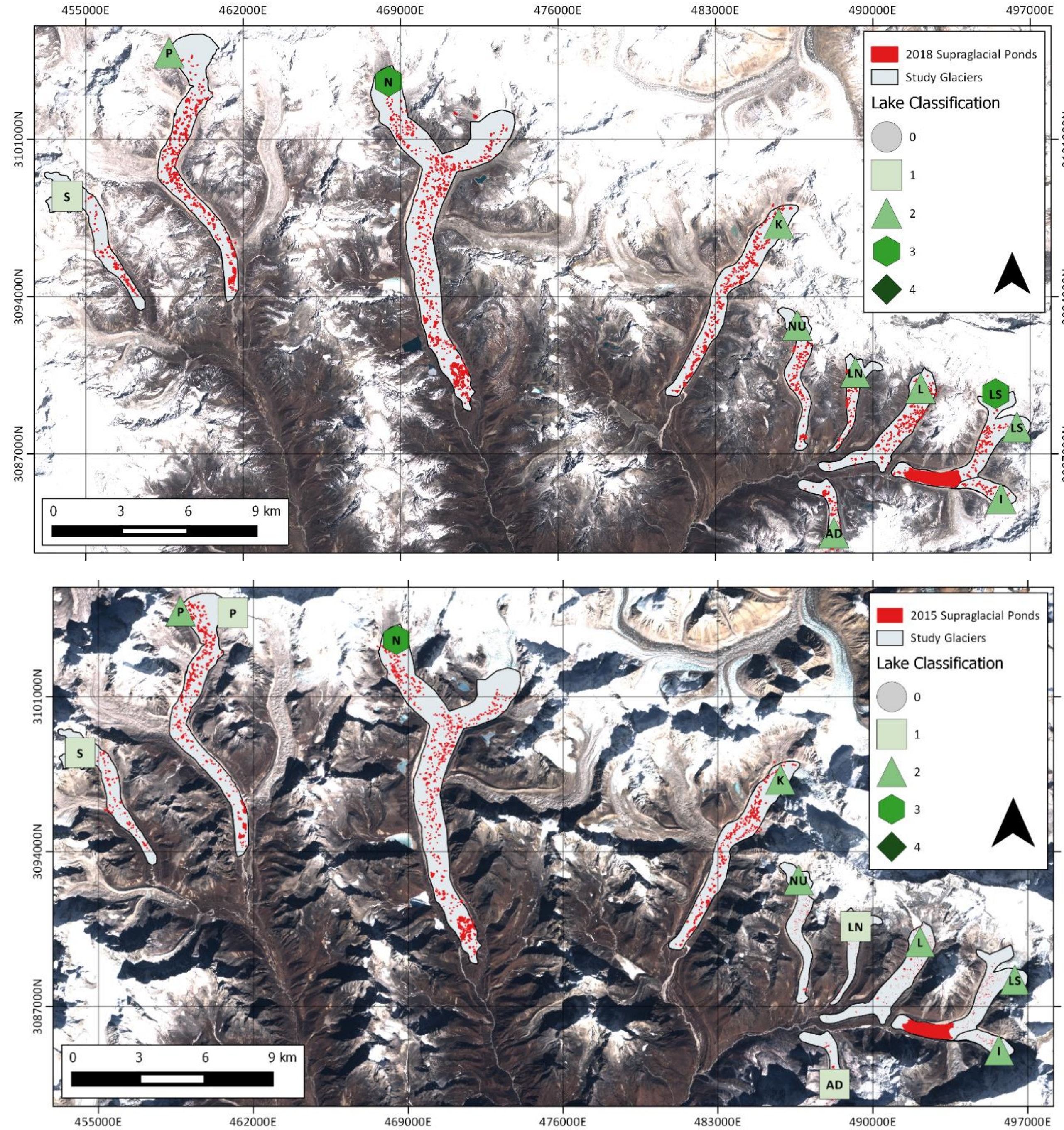

FIGURE 10: STAGE OF LAKE DEVELOPMENT CHANGE OBSERVED OVER THE STUDY PERIOD, FROM 2015 (BOTTOM) TO 2018 (TOP). AD- AMA DABLAM GLACIER, I- IMJA GLACIER, K- KHUMBU GLACIER, N- NGOZUMPA GLACIER, NU- NUPTSE GLACIER, L- LHOTSE GLACIER, LN- LHOTSE NUP GLACIER, LS- LHOTSE SHAR GLACIER, P- PANGBUNG GLACIER, S- SUMNA GLACIER. BACKGROUND IMAGE IS 2018 SENTINEL-2 IMAGE (AVAILABLE FROM USGS AT HTTP://EARTHEXPLORER.USGS.GOV/).

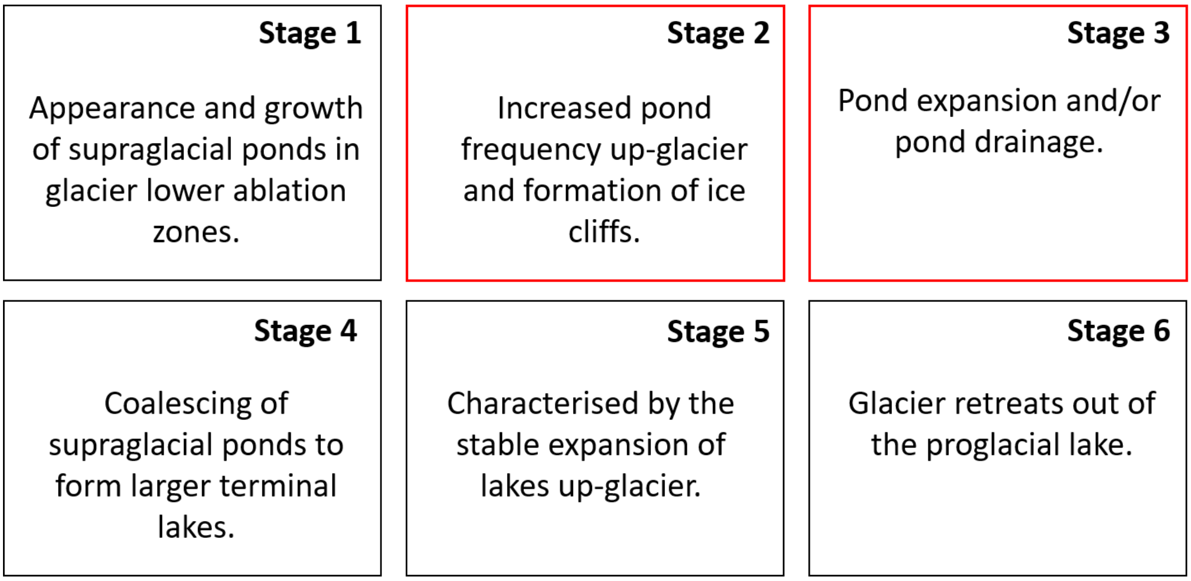

FIGURE 11: UPDATED KOMORI (2008) AND ROBERTSON (2012) CONCEPTUAL LAKE CLASSIFICATION MODEL, TO INCLUDE 2 ADDITIONAL STAGES ACCOUNTING FOR 'IN-STAGE' CHANGES OBSERVED IN THIS STUDY; STAGE 2: RECOGNISES THE ROLE OF ICE-CLIFFS AND CHANGES IN SURFACE DEBRIS LEADING TO POND FORMATION AND DECAY; STAGE 3: GIVES MARGINAL BASED EXPANSION OF PONDS AND POND DRAINAGE EVENTS THEIR OWN CATEGORY (AFTER KOMORI 2008; ROBERTSON 2012; MERTES ET AL., 2016).