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Hydrology of debris-covered glaciers in High Mountain Asia

Katie E. Miles[1*], Bryn Hubbard[1], Tristram D. L. Irvine-Fynn[1], Evan S. Miles[2], Duncan J. Quincey[3]
and Ann V. Rowan[4]

1. Centre for Glaciology, Department of Geography and Earth Sciences, Aberystwyth University, Aberystwyth, UK

2. Swiss Federal Research Institute WSL, 8903 Birmensdorf, Switzerland

3. School of Geography, University of Leeds, Leeds, UK

4. Department of Geography, University of Sheffield, Sheffield, UK

** Correspondence to: kam64@aber.ac.uk*

Key words

Glaciers; debris-covered glaciers; glacier hydrology; High Mountain Asia

Abstract

The hydrological characteristics of debris-covered glaciers are known to be fundamentally different from those of clean-ice glaciers, even within the same climatological, geological and geomorphological setting. Understanding how these characteristics influence the timing and magnitude of meltwater discharge is particularly important for regions like High Mountain Asia, where downstream communities rely on this resource for sanitation, irrigation and hydropower. The hydrology of debris-covered glaciers is relatively complex: rugged surface topographies typically route meltwater through compound supraglacial-englacial systems involving both channels and ponds, as well as pathways that remain unknown. Low-gradient tongues that extend several kilometres retard water conveyance and promote englacial storage. Englacial channels are frequently abandoned and reactivated as water supply changes, new lines of permeability are exploited, and drainage is captured due to high rates of surface and subsurface change. Seasonal influences, such as the monsoon, are superimposed on these distinctive characteristics, reorganising surface and subsurface drainage rapidly from one season to the next. Recent advances in understanding have mostly come from studies aimed at quantifying and describing supraglacial processes; little is known about the subsurface hydrology, particularly the nature (or even existence) of subglacial drainage. In this review, we consider in turn the supraglacial, englacial, subglacial, and proglacial hydrological domains of debris-covered glaciers in High Mountain Asia. We summarise different lines of evidence to establish the current state of knowledge and, in doing so, identify major knowledge gaps. Finally, we use this information to suggest priorities for future hydrological research at High Mountain Asian debris-covered glaciers, and how they may influence our ability to be able to make long-term predictions of changes in the water they supply.

1. Introduction

Debris-covered glaciers have gained increased research attention over recent years, partly in recognition of their role as water sources for large parts of the world's population (Scherler et al., 2011), and partly because they host a range of distinctive features, driven by processes that are largely absent at their clean-ice counterparts. Definitions for what constitutes a 'debris-covered glacier' vary widely (e.g. Anderson, 2000; Kirkbride, 2011), but here we define them to be glaciers with a largely continuous layer of supraglacial debris over most of the ablation area, typically increasing in thickness towards the terminus (Figure 1). Debris can be supplied to such glaciers by avalanches, rockfalls and small landslides from local mountainsides onto the glacier surface (Figure 2, 3A), thrusting from the bed, dust blown from exposed moraines, or solifluction from (ice-cored) moraines (Dunning et al., 2015; Evatt et al., 2015; Gibson et al., 2017b; Hambrey et al., 2008; Kirkbride and Deline, 2013; Kirkbride and Warren, 1999; Rowan et al., 2015; Spedding, 2000; van Woerkom et al., 2019). The surface debris layer can range in thickness from scattered particles to several metres, including large rocks and substantial boulders (Figure 3C and D) (Inoue and Yoshida, 1980; McCarthy et al., 2017; Nicholson et al., 2018).

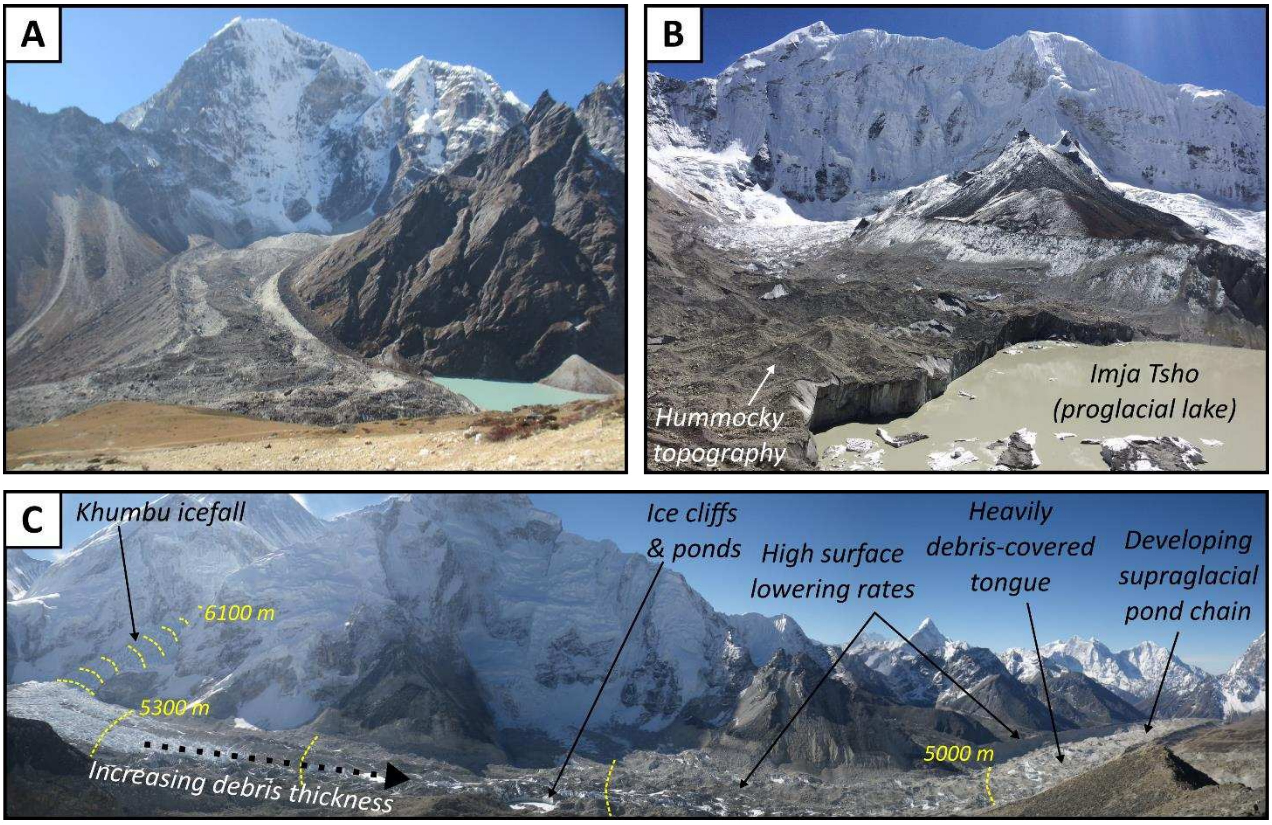

Figure 1 – Debris-covered glaciers in the Sagarmatha National Park, Nepal Himalaya, annotated with some of the features distinctive to High Mountain Asian debris-covered glaciers. ***A)*** *Chola Glacier (image width is ~1.5 km across the glacier terminus and lake).* ***B)*** *Imja Glacier, showing the terminus and calving front (~0.75 km width) into Imja Tsho, looking towards the accumulation area of the tributary Amphulapcha Glacier.* ***C)*** *Khumbu Glacier, showing the upper ablation area (clean-ice flowing from the Khumbu Icefall) to the left and the ~10 km long lower ablation area (debris-covered tongue) to the right; dashed yellow lines are 100 m contours.*

Debris-covered glaciers are present in nearly all of Earth's glacierised regions, with a particularly large concentration in High Mountain Asia (Bolch et al., 2012; Scherler et al., 2018, 2011). Around 25% of Earth's population is dependent on melted glacier ice and/or seasonal snow for drinking water, irrigation or hydroelectric power (Immerzeel et al., 2010); glacial runoff in High Mountain Asia is an important component of streamflow, particularly for reducing seasonal water shortages (Bolch et al., 2019; Pritchard, 2019; Scott et al., 2019). Glacier mass loss in response to climate warming is currently increasing river discharge and contributions to sea level (IPCC, 2019; Lutz et al., 2014; Radić et al., 2014; Shea and Immerzeel, 2016), but studies simulating future scenarios universally predict long-term reductions in flow, perhaps as soon as 2050 in central Asia (Barnett et al., 2005; Bolch et al., 2012; Lutz et al., 2014; Ragettli et al., 2016b; Sorg et al., 2012). This passing of 'peak water' threatens future water security in many regions, particularly across High Mountain Asia (Bolch et al., 2019; Eriksson et al., 2009; Hannah et al., 2005; Huss and Hock, 2018; Immerzeel et al., 2010; Winiger et al., 2005). A decrease in discharge from the Indus and Brahmaputra rivers alone is estimated to affect 260 million people (Immerzeel et al., 2010).

The long-term response of debris-covered glaciers to changing climatic conditions is strongly non-linear and reflects complexities relating to spatial variability in debris concentration and climatic controls integrated over at least several decades (Benn et al., 2012; Vaughan et al., 2013). A decadal trend of surface lowering, stagnation and glacier mass loss has already been observed on many debris-covered glaciers across High Mountain Asia (Bolch et al., 2012, 2011; IPCC, 2019; Kääb et al., 2012; Pellicciotti et al., 2015; Scherler et al., 2011) as a result of warmer air temperatures and weaker monsoons (Pieczonka et al., 2013; Thakuri et al., 2014). However, predictions of mass loss from individual glacierised regions vary hugely. For example, in the Everest region of the Himalaya, estimates of ice mass loss by 2100 vary from ~10% (Rowan et al., 2015), through 50% (Soncini et al., 2016), to 99% in extreme scenarios (warming of ~3°C) (Shea et al., 2015). Model outputs also vary spatially at a regional scale (e.g. Chaturvedi et al., 2014; Kraaijenbrink et al., 2017; Zhao et al., 2014). Such predictions depend sensitively on the precise climate scenario used, but a number of key knowledge gaps exist concerning the character of debris-covered glaciers and the processes influencing their varied geometrical response to climate change (Benn et al., 2012; Bolch et al., 2012; Huss, 2011; Scherler et al., 2011).

Understanding how meltwater is produced, transported, and stored within High Mountain Asian debris-covered glaciers is therefore imperative. However, hydrological research has been severely limited by the remoteness and inaccessibility of such glaciers. There is growing recognition that the configuration and efficiency of water routing across and through debris-covered ice is distinctively different from that of clean-ice glaciers, even within the same glacial system – first shown by a recent study on Miage Glacier, a debris-covered glacier in the European Alps (Fyffe et al., 2019b). Debris-covered glacier surfaces are complex, often characterised by hummocky, rugged topography with a shallow (or even reversed) longitudinal surface gradient (Figures 1 and 2), with depressions capable of storing meltwater for both short and long periods within nested catchments of varying spatial scales. These features, and a host of others, are particularly prominent in High Mountain Asia (Figure 1), and provide a setting that strongly influences the nature of hydrological systems in this region (Benn et al., 2017; Miles et al., 2019).

In this review, we consider the current state of knowledge of debris-covered glacier hydrological systems in High Mountain Asia. Four hydrological domains are considered in turn: supraglacial (Section 2), englacial (Section 3), subglacial (Section 4), and proglacial (Section 5). Within each section, we summarise existing research and understanding of debris-covered glacier hydrological systems and then address key remaining knowledge gaps. Figure 2 provides a reference conceptual diagram of a High Mountain Asian debris-covered glacier, with each hydrological feature encompassing both known and unknown elements of each domain. Finally, in light of the above, we propose future research directions concerning the hydrology of debris-covered glaciers (Section 6). This review is intended to complement existing reviews of clean-ice valley glacier hydrology (e.g. Fountain and Walder, 1998; Hubbard and Nienow, 1997; Irvine-Fynn et al., 2011; Jansson et al., 2003) and, while we define the spatial scope as High Mountain Asia, much existing research has been carried out in the Himalaya (particularly Nepal), from where the review and our illustrations of many of the key elements draw strongly.

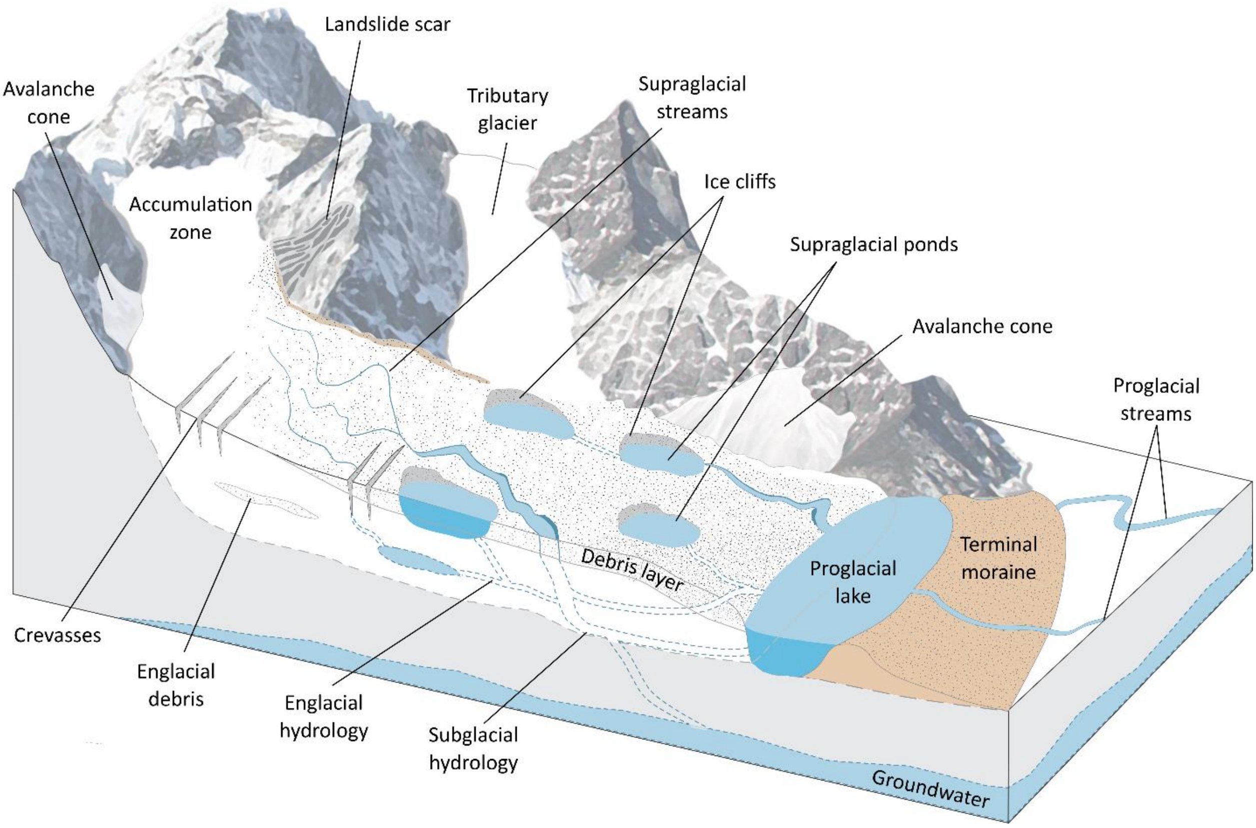

Figure 2 – A conceptual illustration of the main landscape and hydrological features of a typical debris-covered glacier in High Mountain Asia.

2. Supraglacial hydrology

2.1 Supraglacial zone

2.1.1 Meltwater generation

Meltwater is produced on debris-covered glaciers through ablation of surface ice and snow, with the spatial pattern of melt complicated by the surface debris extent, thickness and lithological characteristics (Figures 1 and 3). A debris layer shallower than a critical thickness, typically ~50 mm, decreases albedo and thus increases the ablation rate compared to debris-free ice. The ablation rate peaks at a debris thickness of ~2–5 mm, known as the effective thickness (Adhikary et al., 2000; Evatt et al., 2015; Inoue and Yoshida, 1980; Juen et al., 2014; Lejeune et al., 2013; Nicholson and Benn, 2013, 2006; Østrem, 1959; Singh et al., 2000; Takeuchi et al., 2000). The exact values of the critical and effective thickness strongly depend on the thermal conductivity of the debris (Figure 4), which can vary widely both across a glacier surface and in time according to whether the debris is wet or dry (Casey et al., 2012; Collier et al., 2015, 2014; Gibson et al., 2017b; Nicholson and Benn, 2013; Pelto, 2000). In contrast, a debris layer thicker than > ~50 mm insulates the ice from incoming solar radiation, inhibiting the receipt of surface energy at the ice-debris interface and thus reducing the melt rate (Figure 4). Beneath a debris thickness of 250–300 mm, ice becomes almost fully insulated from daily surface energy fluxes, with only longer-term changes in surface energy balance reaching the underlying debris-ice interface (Bocchiola et al., 2015; Brock et al., 2010; Conway and Rasmussen, 2000; Nicholson and Benn, 2013; Østrem, 1959; Reid and Brock, 2010). Variations in ablation according to these factors represent an important first-order control on glacier surface morphology and are partially responsible for the characteristic hummocky topography superimposed on a shallow or concave (reversed gradient) debris-covered glacier surface profile (Figure 1).

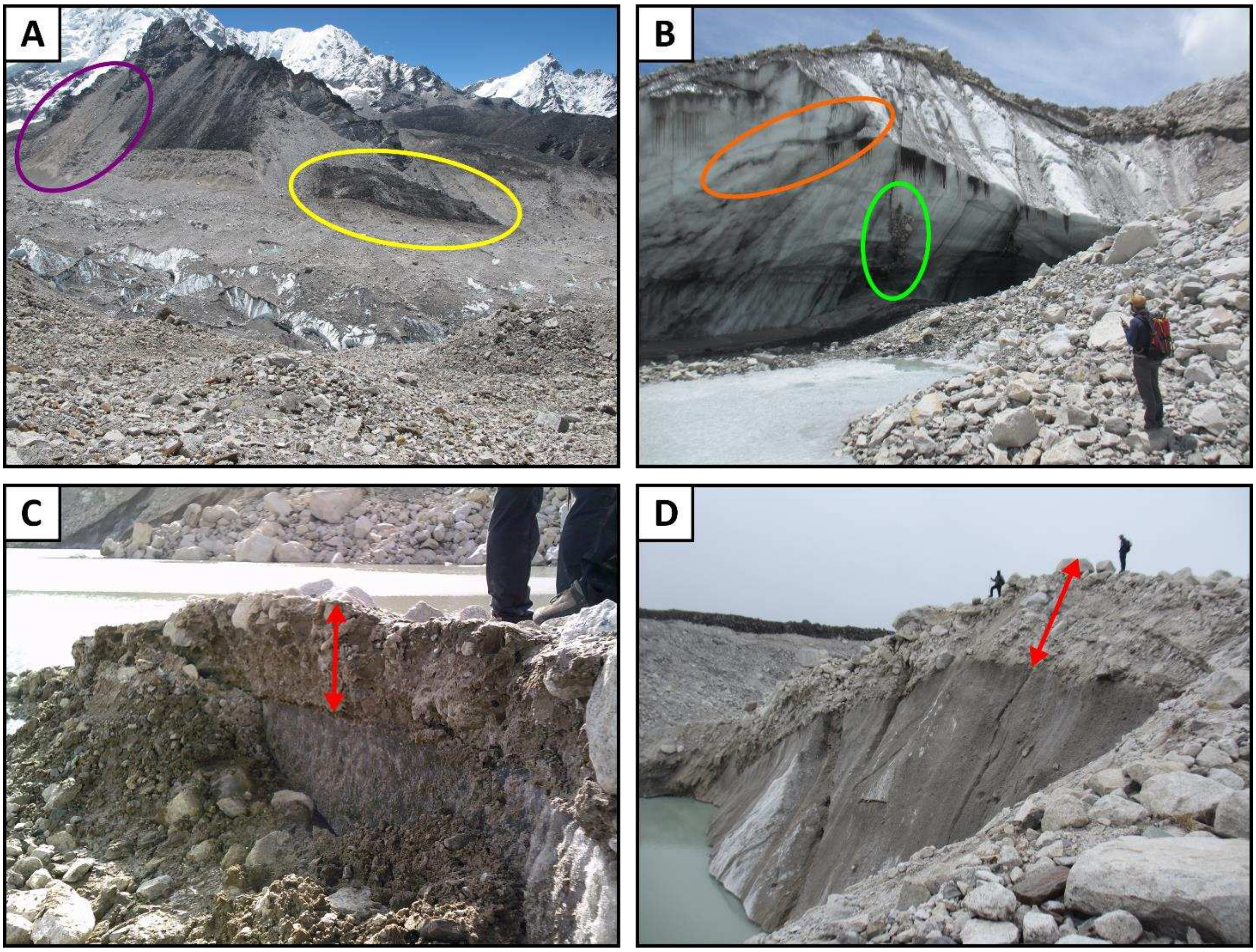

Figure 3 – Images illustrating variations in debris thickness on Khumbu Glacier, Nepal Himalaya: ***A)*** *a landslide scar (yellow circle, ~500 m wide) and unstable rock faces (purple circle) providing*

debris to the glacier surface; image is taken looking east across the surface of Khumbu Glacier, and the debris layer above ice cliffs can also be seen. ***B)*** *an ice cliff with entrained debris (green circle), debris-rich ice layers (orange circle), and a moderately-thick (~1–2 m) surface debris layer;* ***C)*** *a thin (~20 cm; red arrow) surface debris layer above ice adjacent to a supraglacial pond; and* ***D)*** *a thick (> 5 m; red arrow) surface debris layer above an ice cliff.*

Counteracting the influence of a thick surface debris layer, the ablation rate of debris-covered glaciers is enhanced by the presence of supraglacial ponds (Section 2.1.2) and ice cliffs (Figure 3B and D). The latter form by slumping of debris from steep slopes, calving at supraglacial pond margins (Section 2.1.2), or the collapse of englacial voids (Section 3.1), all of which expose steep, bare ice (Figure 3B) or thinly debris-covered (Figure 3D) faces at the glacier surface (Benn et al., 2012, 2001; Sakai et al., 2002; Thompson et al., 2016). The melting of ice cliffs is responsible for a substantial proportion of debris-covered glacier ablation (Brun et al., 2016; Buri et al., 2016b; Han et al., 2010; Juen et al., 2014; Reid and Brock, 2014; Sakai et al., 2002, 2000; Thompson et al., 2016), accounting for up to 69% of the total ablation of debris-covered areas whilst covering as little as 2% of the total glacier area, exhibiting melt rates often 10–14 times higher than beneath debris-covered ice (Immerzeel et al., 2014; Sakai et al., 1998). Where ice cliffs are associated with supraglacial ponds, there is further potential for increased melting through undercutting and calving processes (Brun et al., 2016; Buri et al., 2016a; Miles et al., 2016; Röhl, 2008; Thompson et al., 2016). Taken together, ice cliff and pond systems contribute significantly to the surface lowering of debris-covered glaciers where the debris layer is thinner in the central ablation area (King et al., 2017; Nuimura et al., 2012; Pellicciotti et al., 2015; Ragettli et al., 2016a; Thompson et al., 2016; Watson et al., 2017), contributing to the inverted mass balance regime typical of High Mountain Asian debris-covered glaciers.

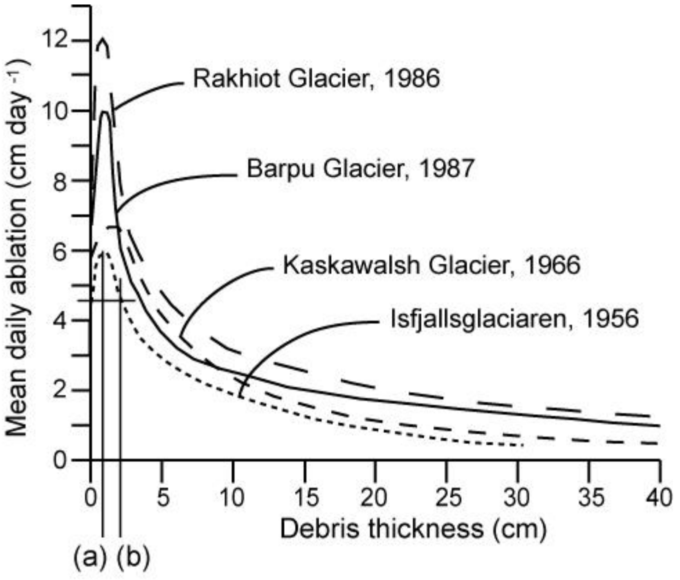

Figure 4 – Østrem curve examples from Nicholson & Benn (2006, and citations therein), showing variations in the relationship between debris thickness and ice ablation on different glaciers. (a) notes the debris thickness at which maximum melt occurs, and (b) marks the debris thickness at which melt becomes inhibited compared to that of clean ice on different glaciers (indicated on both for Isfjallsglaciaren).

2.1.2 Meltwater storage

Supraglacial ponds (Figure 5), a term used here to include larger water bodies elsewhere sometimes referred to as lakes, are common and important features on debris-covered glaciers, particularly those with recent surface lowering. Ponds are generally absent from clean-ice valley glaciers but are prevalent on low-gradient areas of ice sheet margins (Chu, 2014; Sundal et al., 2009). Similarly for debris-covered glaciers, the most important control on the location of supraglacial pond formation is a low glacier surface slope (Miles et al., 2017b; Quincey et al., 2007; Reynolds, 2000; Sakai, 2012; Sakai et al., 2000; Sakai and Fujita, 2010; Salerno et al., 2012). A surface gradient of ≤ 2° is considered to promote the development of larger ponds, while smaller isolated and transient ponds are considered more likely on steeper slopes (Miles et al., 2017b; Quincey et al., 2007; Reynolds, 2000). The upglacier slope has also been shown to have an influence, being inversely correlated to the total area of lakes downglacier (Salerno et al., 2012).

Glacier velocity and motion type also exert controls over supraglacial pond location. An increase in lake concentration is common towards the termini of debris-covered glaciers, areas that are typically characterised by (very) low surface velocities (Kraaijenbrink et al., 2016b; Miles et al., 2017b; Quincey et al., 2007; Sakai, 2012; Salerno et al., 2015, 2012). A decrease in velocity towards the glacier terminus and ice inflow at the confluences of flow units (Kraaijenbrink et al., 2016b) causes compressive flow, which tends to close crevasses and drive water back to the surface, as well as limiting effective drainage from the glacier surface (Kraaijenbrink et al., 2016b; Miles et al., 2017b). The thinning and stagnation of debris-covered glacier termini may also enhance meltwater production, further promoting the formation of ponds (Salerno et al., 2015; Thakuri et al., 2016).

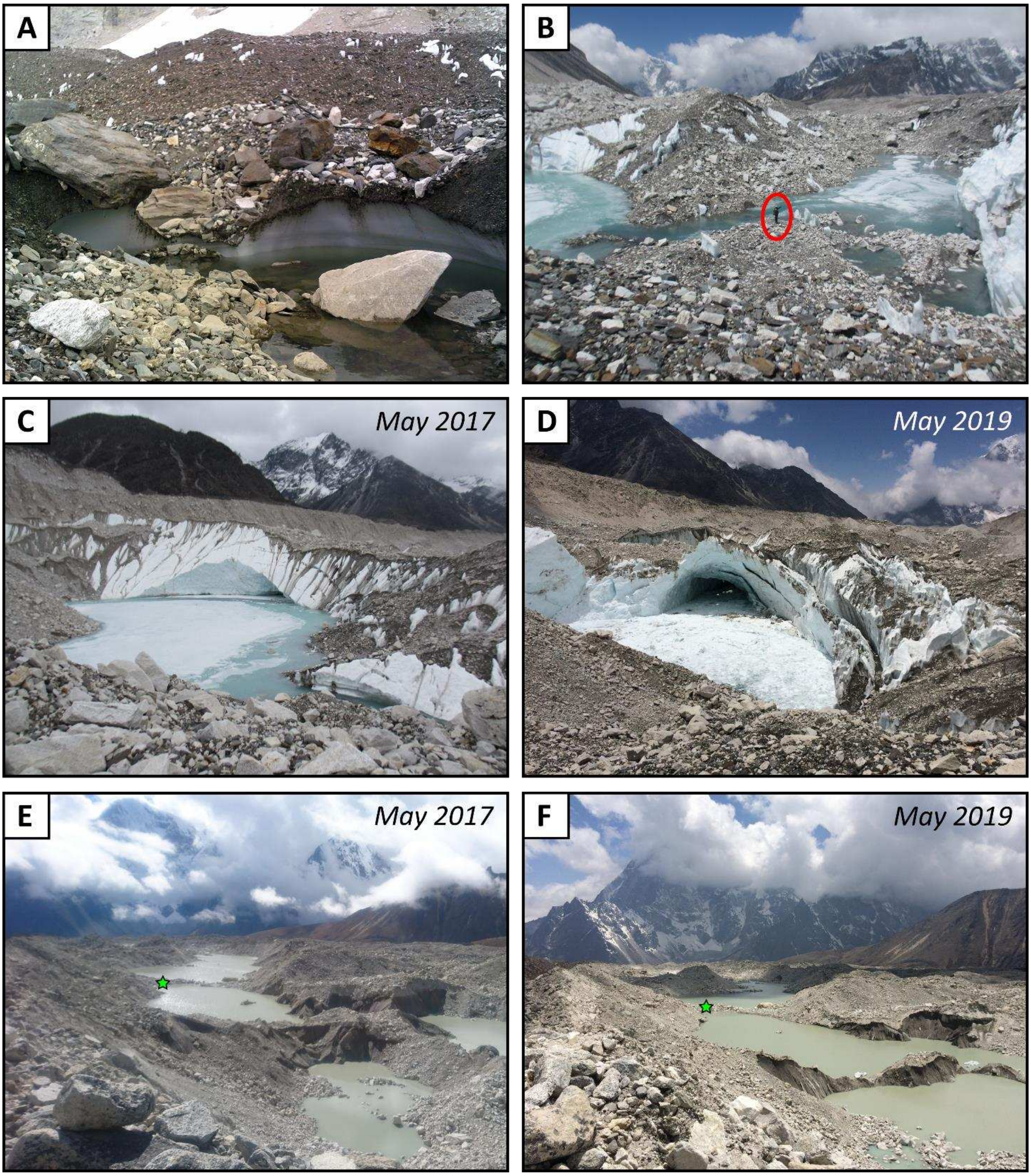

Figure 5 – Examples of supraglacial pond size and temporal changes on Khumbu Glacier, Nepal Himalaya. Ponds range in diameter from: ***A)*** *several metres;* ***B)*** *tens of metres (person circled in red for scale);* ***C)*** *and* ***D)*** *hundreds of metres;* ***E)*** *and* ***F)*** *several kilometres. A) and B) are located in the upper ablation area. C) and D) show the same pond-cliff-cave system in the mid-ablation area two years apart, with notable expansion of the cave via undercutting and calving. The pond, which has reduced in area (likely partly drained), was filled with a large amount of small, calved ice blocks in May 2019 and large cracks in the cliff system suggest further imminent large-scale calving. E) and F) show the expanding linked supraglacial pond chain at the terminus, also two years apart (green star indicates the same location as images were taken from slightly different positions). Pond*

growth and coalescence has progressively eroded the hummocks that used to separate these ponds. Higher melt rates are indicated by the covering of ice cliffs in fine debris ('dirty ice').

Initial supraglacial pond growth occurs through subaqueous melting at the base of any slight depression (Chikita et al., 1998; Mertes et al., 2016; Miles et al., 2016; Stokes et al., 2007; Thompson et al., 2012). Water accumulates and is heated by incoming solar radiation, causing the pond to warm. For example, Chikita et al. (1998) measured a maximum temperature of ~5°C at a supraglacial lake surface on Trakarding Glacier, Nepal Himalaya. Excess energy is thus available for lateral and vertical ablation wherever pond water is in contact with ice, increasing the pond size, steepening marginal slopes and mobilising debris to expose bare ice (Figure 5E and F) (Stokes et al., 2007). Furthermore, mixing of pond stratification by inflowing meltwater on Koxkar Glacier, Tien Shan, has been shown to increase the temperature (by ~4°C) and density of the pond (Xin et al., 2012). Here, the warmed surface water sinks to the pond base and increases the potential for subaqueous melting; a process that can also be induced by wind-driven currents (Chikita et al., 1998).

Supraglacial ponds surrounded by ice cliffs tend to be larger and deeper than those without cliffs (Watson et al., 2018), as the ice cliffs facilitate pond growth by subaerial melting and backwasting, particularly during the monsoon melt season (Röhl, 2008; Steiner et al., 2019). Where warm surface pond water meets glacier ice, it can undercut the cliff beneath the waterline; progressive undercutting and thermo-erosional notch development may then lead to calving of the ice cliff and pond expansion (Figure 5C and D) (Chikita et al., 1998; Kirkbride and Warren, 1997; Mihalcea et al., 2006; Miles et al., 2016; Röhl, 2008, 2006; Sakai et al., 2009). Conversely, where the subaqueous and ice cliff melt rates are similar, the ice cliff will persist and backwaste stably (Brun et al., 2016; Buri et al., 2016a; Miles et al., 2016). Calving is most effective at larger ponds (Röhl, 2008), in particular where the fetch is greater than 20 m and the water temperature is 2–4°C (Sakai et al., 2009). Calving events cause further mixing of pond layers, driving warmer surface water towards the base and again enhancing basal melting: greatest supraglacial pond deepening rates of have been shown to occur adjacent to the tallest calving ice cliffs (Thompson et al., 2012). Although sedimentation from ice cliffs and inflowing water can reduce pond depth, this effect is often outstripped by ablation (Thompson et al., 2012).

A pattern of supraglacial pond evolution into moraine-dammed lakes has been observed for some ponds on debris-covered glaciers in High Mountain Asia. Supraglacial ponds form initially as 'perched ponds', isolated above the englacial drainage network (Benn et al., 2012). As these ponds increase in area and depth, they evolve from perched to base-level features, where the base-level is determined by the height at which water leaves the glacial system (usually the elevation of a spillway through the terminal moraine or the glacier bed, if water is transported there) (Mertes et al., 2016; Thompson et al., 2012). However, differing sub-catchments may have differing base-levels defined by other hydrological features such as moulins, which can result in a stepped hydrological cascade based on several local base-levels. Alternatively, the presence of a groundwater system can result in a regional base-level. Over an extended period of glacier recession, an increasing number of supraglacial ponds form and grow over time, creating a chain of terminus-base-level ponds that eventually coalesce (Figure 5E and F) (Sakai, 2012; Salerno et al., 2012). The growth of base-level ponds is not limited by periodic drainage, potentially allowing dramatic increases in area, particularly through calving (Benn et al., 2001; Sakai, 2012; Thompson et al., 2012). If meltwater cannot escape from the system, pond expansion and coalescence may eventually lead to the formation of a single base-level moraine-dammed proglacial lake at the glacier terminus (Section 5.1.1) (Mertes et al., 2016) that will continue to expand both upglacier and downwards by ice melt.

Various stages of this supraglacial pond evolution are simultaneously present on many High Mountain Asian debris-covered glaciers. An increase in supraglacial pond area and proglacial lake formation, assumed to be in response to a warmer climate and glacier surface lowering, has been observed in recent decades in, for example, the Tien Shan (Wang et al., 2013), Bhutan Himalaya (Ageta et al., 2000; Komori, 2008) and Nepal Himalaya (Benn et al., 2000; Watson et al., 2016). Within the Hindu-Kush Himalaya, a clear divide has appeared between the East, where there are a greater number of larger ponds that have grown between 1990–2009 and become increasingly proglacial, and the West, where already generally smaller supraglacial ponds have been decreasing further in area (Gardelle et al., 2011). However, local variations do occur and the pattern is not universal (e.g. Steiner et al., 2019).

As isolated perched ponds grow, they can deepen such that they become connected to the englacial system by intersecting englacial flow pathways, and drain (Benn et al., 2001; Qiao et al., 2015; Röhl, 2008; Watson et al., 2018, 2016; Wessels et al., 2002), temporarily halting further pond expansion (Mertes et al., 2016). Pond drainage is promoted in zones of higher local surface velocity and strain rates, connecting the supraglacial and englacial drainage networks and resulting in smaller-sized ponds (Miles et al., 2017b). However, as noted above, ponds are generally more likely to form in areas with lower surface velocities. Ponds may also drain by preferentially exploiting inherited structural weaknesses such as (sediment-filled) crevasse traces, crevasses and englacial channels that have been forced closed by longitudinal compression, allowing drainage by hydrofracture (the penetration of a water-filled crevasse through an ice mass assisted by the additional pressure of the water at the crevasse tip) (Benn et al., 2017, 2012, 2009; Gulley and Benn, 2007; Miles et al., 2017b). Alternatively, perched ponds may drain by overspilling, when a channel is melted into the downstream end of a pond. If, during drainage, such a channel incises faster than the pond lowers then unstable and potentially catastrophic drainage can result (Qiao et al., 2015; Raymond and Nolan, 2000). However, analyses on Lirung Glacier, Nepal Himalaya, provided strong evidence for continuous inefficient drainage of supraglacial ponds, likely into debris-choked englacial conduits (Miles et al., 2017a).

A periodic cycle of pond expansion and drainage may occur until the pond becomes large enough to become permanently connected to the englacial system, and thus more stable due to inputs of meltwater from streams and other ponds located farther upglacier (Benn et al., 2001; Miles et al., 2017a; Wessels et al., 2002). An abundant supply of meltwater from the ice surface or the wider drainage system is indicated by ponds with a high suspended sediment concentration (Takeuchi et al., 2012). A seasonal pattern of supraglacial pond filling and drainage has been observed at seven glaciers in the Tien Shan, with 94% of observed ponds draining during the monsoon every year between 2013–2015 (Narama et al., 2017). Similar cycles were reported for five glaciers in Langtang Valley, Nepal Himalaya, where the maximum ponded area between 1999–2013 occurred early in the melt season, subsequently decreasing as ponds drained or froze (Miles et al., 2017b). Conversely, larger ponds have been observed to drain incompletely and separate into multiple smaller ponds, subsequently refilling to re-form one large pond (Benn et al., 2001; Miles et al., 2017b; Wessels et al., 2002). Warmer spring temperatures have been noted to correlate with a greater number of drainage events later the same year, likely due to greater meltwater inputs earlier in the year triggering redevelopment of the subsurface drainage system (Qiao et al., 2015).

Supraglacial ponds are responsible for a large proportion of debris-covered glacier ablation, absorbing heat up to 14 times more quickly than the debris-covered area. In the Langtang Valley, Nepal, this accounted for 12.5% of catchment ice loss (E. S. Miles et al., 2018b). However, linked supraglacial pond chains have been suggested to provide only a small proportion of total glacier proglacial discharge (Irvine-Fynn et al., 2017; Miles et al., 2019), primarily storing meltwater and thus increasing the potential for enhanced ablation. Ponds have a strongly positive surface energy balance, with ≥ 50% of their absorbed energy released with the melt output from the pond and contributing to internal melting along supraglacial and englacial conduits (Miles et al., 2016; Sakai et al., 2000). This in turn may lead to englacial roof collapse and the formation of new ponds (Benn et al., 2012; Miles et al., 2017a; Sakai et al., 2000), resulting in a net glacier-wide increase in ablation. The increasing presence of ponds has been described as the clearest indicator of the influence of climate change on debris-covered glaciers (Salerno et al., 2012).

2.1.3 Meltwater transport

Supraglacial streams (Figure 6) on High Mountain Asian debris-covered glaciers vary widely in prevalence, size and length. To exist and persist, a supply catchment is required (Benn et al., 2017; Gulley et al., 2009a) and the rate of stream incision, driven by thermal erosion, must outpace the rate of surface lowering (Marston, 1983). Such conditions may be promoted beneath thicker debris that suppresses surface ablation in the lower ablation area (Benn et al., 2017), yet observations of streams in this region are rare, likely due to the hummocky topography both limiting the size of supraglacial catchments (Fyffe et al., 2019b) and preventing any streams that do form from persisting for long distances (Benn et al., 2017). Farther upglacier, often under conditions of strong longitudinal extension associated with ice falls, open crevasses are common and also suppress supraglacial stream development (Benn et al., 2017). Most supraglacial streams have therefore been observed in the upper to mid-ablation area (Figure 6A-D) (Gulley et al., 2009a; Miles et al., 2019), downglacier of crevasse fields but sufficiently far upglacier that the hummocky topography is not overly pronounced and the debris layer is thin (Section 2.1.1).

A perennial supraglacial stream has been present in the upper ablation area of Khumbu Glacier, Nepal Himalaya, for over 14 years (Figure 6A-D) (Gulley et al., 2009a; Miles et al., 2019). This stream and its smaller tributaries originate just downglacier of the Khumbu icefall, where the surface gradient decreases dramatically (Figure 1). The low surface gradient of the ablation area results in this channel having high sinuosity (Miles et al., 2019). As streams transfer meltwater downglacier, they can incise effectively into the glacier surface (Figure 6B and C); one channel had melted 5–10 m deep by the time it reached the lower ablation area (Gulley et al., 2009a; Iwata et al., 1980). Such incision is evident where channel sides have ablated more slowly than the surrounding glacier surface, leaving walls of horizontally-notched ice showing previous high water-levels (Figure 6C). Supraglacial streams may drain into debris-covered glaciers through crevasses or moulins (Gulley et al., 2009a; Iwata et al., 1980), or through ‘cut-and-closure’ (see Section 3.1) (Gulley et al., 2009a; Jarosch and Gudmundsson, 2012). Relict channels abandoned by continued incision can often be exposed on the surface as a result of spatially variable surface lowering (Figure 6D).

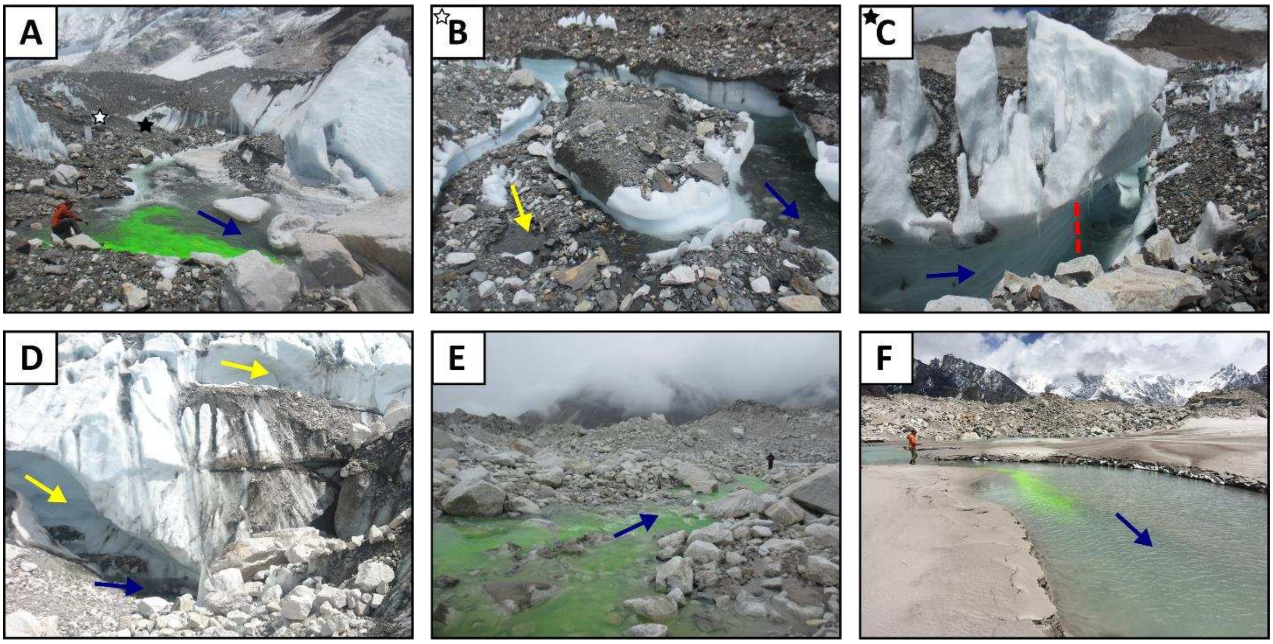

Figure 6 – Examples of supraglacial streams on Khumbu Glacier, Nepal Himalaya, in: ***A-C)*** *the upper ablation area, incised into the ice beneath the debris layer. Blue arrows indicate water flow direction; yellow arrows indicate abandoned/relict channels. The supraglacial stream in A) is extensive and very well developed, transporting large volumes of meltwater efficiently. B) and C) are upstream of A) (white and black star, respectively): B) shows a relict, debris-filled meander bend which has been superseded by a more direct channel; C) shows multiple levels of stream incision (grooves indicated by red dashed line, ~1 m high);* ***D)*** *the mid-ablation area, where the same incised channel becomes englacial through cut-and-closure after several hundred metres of progressive downcutting, visible from the multiple relict levels (channel drop in the image is ~10 m);* ***E)*** *and* ***F)*** *the lower ablation area. The channel in E) is a short stretch between a supraglacial pond and a shallow moulin, flowing over the debris layer. The stream in F) flows into a breach in the lateral moraine to form the proglacial stream; here it has eroded into the sand-like sediment across a basin that seasonally floods.*

Supraglacial streams can undergo rapid pathway changes. Figure 6B shows a debris-filled section of channel, abandoned as meltwater progressively took a more direct route, leaving a central island of protruding ice. This process may have been similar to the formation of an ox-bow lake from a terrestrial river meander bend. However, the abandoned channel section may be reactivated during times of high flow, evidenced by the presence of thick, evenly spread debris deposits in Figure 6B. Farther downglacier, where supraglacial stream observations are rarer, pathway changes have also been witnessed on short timescales (Miles et al., 2019). In Figure 6E, the stream flows into a shallow moulin, yet within 10 days this moulin had collapsed and been abandoned, with the stream routing into a new moulin just upstream. Moulin collapse has been attributed to the highly spatially variable surface lowering and ablation rates on debris-covered glaciers (Miles et al., 2019), while the short timescale suggests that the new moulin exploited an existing weakness in the ice.

2.2 Supraglacial knowledge gaps

Predictions of future mass balance regimes on High Mountain Asian debris-covered glaciers are still uncertain. Surface lowering is leading to an overall increase in debris thickness (Gibson et al., 2017a) and an upglacier emergence of a thin supraglacial debris layer, which will likely further decrease albedo and increase surface meltwater production (thereby increasing surface lowering, potentially leading to a positive cycle until debris thickens sufficiently to insulate the surface) (Kirkbride and Warren, 1999; Stokes et al., 2007). Measuring meltwater production is crucial, but difficult beneath (thin) debris layers, and often impossible where access to the ice-debris interface is not feasible. More broadly, the future evolution of debris-covered glacier surface geometry remains unaddressed, for example, whether meltwater will primarily be transported rapidly off the glacier in channels or stored within large systems of linked supraglacial ponds, thus moderating diurnal proglacial discharge.

On a finer scale, a detailed process understanding of meltwater storage and transport through supraglacial ponds and pond systems is lacking, particularly of water circulation within, between and out of ponds (while often just one discrete conduit output is visible, water has also been observed to seep beneath the debris layer and emerge in unexpected locations (Miles et al., 2019)). There has been little focus on how these links between ponds will change as ponds expand and eventually coalesce. Volumetric measurements of supraglacial ponds are scarce, rendering it difficult to accurately calculate how much meltwater is being stored on the glacier surface. Additionally, little attention has been paid to the effect debris (heated by solar radiation) falling into a pond has on the pond temperature and thus its basal melt rate.

The various pathways and rates of meltwater transport across a debris-covered glacier surface would benefit from greater understanding. For example, supraglacial streams are commonly difficult to discern in debris-covered regions of the glacier surface; this is particularly true for smaller surface streams and diffuse flows, which are less easily located and consequently remain largely unreported. On a smaller scale, the occurrence of some ice ablation beneath even a thick debris layer implies that during much of the ablation season, water must exist between the ice surface and the debris layer (McCarthy et al., 2017), likely as a thin but variable film. However, the planform structure remains unknown, as does transport beneath the debris layer, which subsequently must occur as a saturated surface layer or - initially at least - as small, inefficient rivulets.

Water storage within and below the supraglacial debris layer is likely but unexplored, introducing temporary delays in the transport of meltwater through the system and thus affecting meltwater hydrochemistry (Tranter et al., 2002, 1993), the development of other parts of the drainage network, and proglacial discharge. However, despite its importance in contrasting with standard models of supraglacial hydrology based on research at clean-ice glaciers, small-scale meltwater storage delays remain unknown, which at least partly reflects the difficulty involved in gaining access to the ice-debris interface beneath thick surface debris. Similar issues are present for the hydrology of snowpacks overlying thick debris, yet the extent that the snowpack delays runoff and how much snowmelt enters the hydrological system are similarly unaddressed.

3. Englacial hydrology

3.1 Englacial zone

Exceptionally, englacial channels at High Mountain Asian debris-covered glaciers have been at least as well explored by glaciospeleologists than at clean-ice glaciers. Such exploration has been carried out primarily in the Nepal Himalaya, including at Khumbu Glacier (Gulley et al., 2009a), Ngozumpa Glacier (Benn et al., 2017, 2009; Gulley and Benn, 2007), Ama Dablam and Lhotse Glaciers (Gulley and Benn, 2007), as well as several debris-covered glaciers in the Tien Shan (Narama et al., 2017). Largely on the basis of such studies, Gulley et al. (2009) proposed three formation mechanisms for englacial channels within debris-covered glaciers:

I. Cut-and-closure type conduits appear to be particularly prevalent within High Mountain Asian debris-covered glaciers, relative to clean-ice counterparts. Since the process requires more rapid channel incision than surface ablation, this prevalence could result from the presence of cold surface ice and/or surface debris, both impeding general surface lowering. Under such conditions, incision will continue to the hydrologic base-level of the glacier (Section 2.1.2) (Gulley et al., 2009a; Miles et al., 2019). These conduits may be repeatedly abandoned and reactivated as water supply varies through the year, with channels closing by snow infill and, possibly, ice creep. However, such channels rarely close completely due to their shallow depth, and may contain sediment that provides lines of secondary permeability by which the channel may subsequently be reactivated (Benn et al., 2009; Gulley et al., 2009a; Gulley and Benn, 2007). Cut-and-closure conduits have been reported on Khumbu (Gulley et al., 2009a) and Ngozumpa Glaciers (Thompson et al., 2012).

II. Meltwater may aggregate to form englacial channels by exploiting lines/planes of secondary permeability; for example, those left by relict cut-and-closure channels or debris-filled and/or compressed former surface crevasses (Benn et al., 2012; Gulley et al., 2009b; Gulley and Benn, 2007; E. S. Miles et al., 2018a). Along these low-permeability zones, discharge through the icy matrix leads to the development of enlarging lines of preferential flow due to viscous heat dissipation, eventually forming an englacial conduit (Benn et al., 2012).

III. Englacial channels may also form by hydrofracturing (Benn et al., 2012, 2009; Gulley et al., 2009b), though this process is generally restricted to upper, debris-free areas where surface runoff can enter open crevasses (Benn et al., 2012). In the lower ablation area, low surface gradients, low strain and compression reduce the capacity for crevassing. Channel formation by hydrofracturing has been invoked in association with longitudinal crevasses on Khumbu Glacier (Benn et al., 2012, 2009), promoted by the combined

> effect of transverse stresses and high water pressure at the base of supraglacial lakes. Multiple stages of hydrofracture, followed by channel closure through freeze-on, were interpreted from a series of successively lower niches eroded into pond walls (Benn et al., 2009).

If a stream exploits a crevasse for a sufficient time it forms a moulin, as on clean-ice glaciers. Although such instances are rare, steep-gradient moulins have been observed in the upper ablation area of some High Mountain Asian debris-covered glaciers (e.g. Southern Inylchek Glacier, Tien Shan and Baltoro Glacier, Pakistan Karakoram (Narama et al., 2017; Quincey et al., 2009)), and a shallow-gradient moulin reported in the lower ablation area of Khumbu Glacier (Figure 6E) (Miles et al., 2019). Indeed, explored englacial conduits, such as on Khumbu and Ngozumpa Glaciers, also had shallow gradients (Benn et al., 2017; Gulley et al., 2009a; Gulley and Benn, 2007), suggesting predominant formation in these instances by cut-and-closure rather than crevasse exploitation.

Englacial channels have been observed at multiple elevations within High Mountain Asian debris-covered glaciers, often showing numerous levels of incision resulting from sequential supraglacial pond drainage events as the base-level has moved (Gulley et al., 2009a; Gulley and Benn, 2007). According to this model, each conduit has a local base-level (Section 2.1.2), but is only present to a depth coincident with the glacier's contemporary base-level, determined by the height at which water leaves the glacier (Gulley et al., 2009a; Gulley and Benn, 2007). Furthermore, as the surface gradient of the ablation area of debris-covered glaciers is typically very low, the hydraulic gradient (Shreve, 1972) is correspondingly low, encouraging meandering and the formation of sinuous englacial channels (Miles et al., 2019), as observed on Khumbu and Ngozumpa Glaciers (Benn et al., 2017; Gulley and Benn, 2007).

Longer-distance water transport has been inferred through perennial sub-marginal channels located along the edge of debris-covered glaciers, likely formed by cut-and-closure (Benn et al., 2017; Thompson et al., 2016). Such marginal features provide longer-distance and more hydraulically-efficient pathways than conduits within the central glacier, due to the frequent presence of infilled crevasse traces that can be exploited by water flowing at the margins (Gulley and Benn, 2007). Centrally-located englacial conduits may become re-exposed due to lowering of the surrounding surface, routing water back to the surface (Figure 7) (Miles et al., 2019), which may make these conduits more discontinuous, particularly when combined with the commonly hummocky topography (Miles et al., 2017a).

Shallow englacial systems have been observed on High Mountain Asian debris-covered glaciers. These typically consist of short channels (channelised, distributed or a combination), englacial reservoirs and/or shallow moulins, primarily linking supraglacial ponds (Miles et al., 2017a, 2019; Narama et al., 2017). Such linked supraglacial-englacial systems may be created and/or maintained by supraglacial pond drainage into englacial conduits (Gulley and Benn, 2007; Narama et al., 2017). Narama et al. (2017) found that the seasonal drainage cycle of supraglacial ponds on seven Tien Shan glaciers was characterised by a connection to an established englacial drainage system later in the summer; 94% of ponds drained and connected on all three years studied. Englacial conduits may thus play an important role in the life cycles of perched ponds (Benn et al., 2017; Miles et al., 2017a).

The efficiency of deeper englacial drainage networks can vary and may also be influenced by supraglacial pond drainage events. On Dokriani Glacier, Garhwal Himalaya, englacial conduits were inferred to be efficient and active through the entire melt season, with proglacial discharge proportional to supraglacial water production (Hasnain and Thayyen, 1994). Conversely, on Khumbu Glacier, a channelised but inefficient englacial system was inferred in the pre-monsoon season (Miles et al., 2019). This system did not link to the supraglacial pond chain, but was routed to the surface closer to the terminus, suggesting that deep englacial to shallow-englacial-supraglacial links are also possible. While this inefficient englacial system was characterised by slow transport velocities, previous observations of faster transit through Khumbu Glacier during the drainage of a tributary glacier's supraglacial pond implies that this system can adapt rapidly to greater meltwater inputs (E. S. Miles et al., 2018a; Miles et al., 2019).

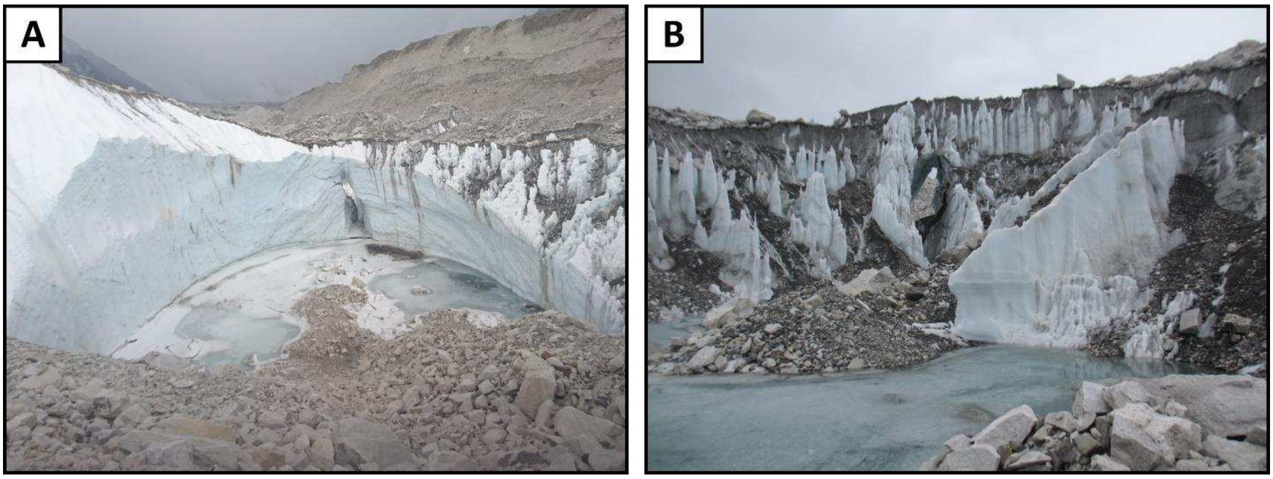

Figure 7 – A relict englacial feature (~10 m in height) in the centre of an ice cliff on Khumbu Glacier, Nepal Himalaya, viewed: ***A)*** *from upglacier, and* ***B)*** *from downglacier, exposed after a drainage event of the associated supraglacial pond. On the downglacier side, tens of metres of surface lowering has occurred and the previously englacial channel is now visible from the surface, meandering and incising for ~200 m further downglacier before flowing into a pond.*

The efficiency of englacial meltwater transport has also been noted to change through the melt season at High Mountain Asian debris-covered glaciers. The influx of large volumes of monsoon precipitation during the summer months may result in the reopening of englacial (and subglacial) conduits, giving potential for considerable englacial ablation (Benn et al., 2012); for a surface pond of 500 m^2, sufficient energy to melt ~2,600 m^3 of temperate ice is released over a single monsoon season (Miles et al., 2016). This additional meltwater ultimately leads to channel erosion (Miles et al., 2017b; Sakai et al., 2000), which may be further enhanced by pond drainage events, as the warmer drained water (Section 2.1.2) conveys large amounts of energy, adding further to total glacier mass loss (Benn et al., 2012; Miles et al., 2016; Sakai et al., 2000; Thompson et al., 2016).

For englacial channels located near the surface, rapid expansion can result in conduit collapse if the ceiling is not sufficiently supported. A relict conduit formed in this way exposes new bare ice faces, including ice cliffs, which may then contribute to more rapid lowering of the glacier surface (Section 2.1.1) (Benn et al., 2017; Kraaijenbrink et al., 2016b; Miles et al., 2016; Sakai et al., 2000; Thompson et al., 2016, 2012). Ablation rates and surface subsidence can be further enhanced if the new depression becomes flooded by that increased meltwater production, supplemented by upglacier inputs, providing new depressions for supraglacial ponds to form or expand and coalesce (Section 2.1.2) (Benn et al., 2012, 2001; Kirkbride, 1993; Kraaijenbrink et al., 2016b; Miles et al., 2017a; Sakai et al., 2000; Thompson et al., 2012).

Meltwater may be stored englacially within debris-covered glaciers, ranging from small shallow englacial reservoirs (Miles et al., 2019) to deeper and potentially larger reservoirs. The latter type has been inferred, for example, on Biafo Glacier, Karakoram Himalaya, at the start of the melt season before the drainage system was reactivated (Hewitt et al., 1989). Similarly, the release of meltwater stored within englacial conduits that became stressed during the transitional pre-monsoon season was partly attributed to the initiation of an outburst flood at Lhotse Glacier (Rounce et al., 2017). Other inferences have been made from supraglacial pond water-level measurements, such as at Imja Tsho, Nepal Himalaya, where the post-melt season lake level was constant despite lower air temperatures and lower precipitation, which would both serve to reduce meltwater production. This situation was explained by recharge from englacially- and subglacially-stored water progressively released over time (Thakuri et al., 2016).

3.2 Englacial knowledge gaps

Despite relatively extensive englacial glaciospeleological exploration, numerous knowledge gaps remain. For example, as at clean-ice glaciers, the thermal regime of the glacier exerts a significant control on the location and formation of an englacial drainage system, yet is unknown for almost all High Mountain Asian debris-covered glaciers. A recent study suggested that the lower area of Khumbu Glacier may primarily comprise temperate ice (K. E. Miles et al., 2018) allowing the existence of a deep englacial drainage system (Miles et al., 2019). However, this research was confined to a single glacier and its representativeness for other debris-covered glaciers in High Mountain Asia remains unknown.

Knowledge of the influence of supraglacial debris on englacial (and subglacial) drainage systems is incomplete. On Miage Glacier, the upglacier cleaner/thinly debris-covered ice was shown to produce an efficient subsurface drainage system to the terminus from the early melt season. In contrast, the heavily debris-covered lower ablation area restricted the development of supraglacial drainage, leading to an inefficient subsurface system that ultimately flowed into the upper glacier's efficient system (Fyffe et al., 2019b). While there are similarities between the drainage system of Miage and the few High Mountain Asian debris-covered glaciers studied, the generally thicker debris layer and much greater prevalence of supraglacial ponds towards the terminus of the latter will additionally influence the hydrological system of such glaciers – an influence that remains unexplored.

Links between the englacial system and other hydrological domains, such as supraglacial-to-englacial transitions (through cut-and-closure channels, weaknesses in the ice and supraglacial pond drainages), would benefit from better understanding. Research into the shallow englacial system is needed, including how much of a distinction there is between shallow englacial and supraglacial systems, considering the rapidly changing surface topography that is typical of High Mountain Asian debris-covered glaciers. Finally, the potential for englacial meltwater storage has received very little attention.

4. Subglacial hydrology

4.1 Subglacial zone

Knowledge of subglacial drainage at High Mountain Asian debris-covered glaciers is limited, although some evidence at least points to the existence of such systems. For example, glaciospeleological investigations indicated that the proglacial stream of a retreating tributary of Khumbu Glacier reached Khumbu's bed (Benn, pers. comm., 2018). This channel was considered to follow the bed for some distance downglacier, similar to the perennial sub-marginal channels present at the edge of the neighbouring Ngozumpa Glacier (Benn et al., 2017; Miles et al., 2019; Thompson et al., 2016). However, this water did not persist subglacially, exiting the glacier supraglacially, likely due to the commonly high hydrological base-level of such glaciers routing the system upwards, possibly following the glacier's cold-temperate transition surface (K. E. Miles et al., 2018; Miles et al., 2019). All other subglacial system information is inferred and discussed briefly below.

The presence of meltwater at the bed has been inferred from surface velocity records from remote sensing (e.g. Quincey et al., 2009) or field-based GPS (e.g. Tsutaki et al., 2019), using inferences similar to those for clean-ice glaciers. Relatively rapid surface velocities in the central areas of glaciers have been recorded during summer months, when melting and rainfall delivery are greatest (Figure 8). Such velocity increases have been interpreted as indicative of basal motion lubricated by subglacial drainage (Benn et al., 2017; Copland et al., 2009; Kääb, 2005; Kodama and Mae, 1976; Kraaijenbrink et al., 2016a; Kumar and Dobhal, 1997; Mayer et al., 2006; Quincey et al., 2009). Similar remote sensing studies of surging debris-covered glaciers, particularly in the Karakoram, have inferred the presence of subglacial water, enabling rapid surface velocities during surge phases (Copland et al., 2009; Quincey et al., 2011; Steiner et al., 2018). For example, a maximum velocity of > 250 m a^{-1} was reported at South Skamri Glacier, Pakistan Karakoram (Copland et al., 2009).

Evidence of channelised subglacial drainage has been provided by the presence of proglacial outlet channels at the terminus of debris-covered glaciers. During the melt season, these discharge large volumes of heavily debris-laden water, implying sediment entrainment during transport along the bed (Quincey et al., 2009). This has also been inferred from comparisons of supraglacial with proglacial solute concentrations on Lirung Glacier, where high proglacial Ca^{2+} and SO_4^{2-} concentrations indicated prolonged contact with reactive debris, inferred to occur during subglacial drainage (Bhatt et al., 2007). Similarly, a perennially-active subglacial system on Dokriani

Glacier was inferred to be connected with the englacial system from proglacial electrical conductivity measurements (Hasnain and Thayyen, 1994).

Variations in subglacial system efficiency have been inferred from studies focusing on the proglacial stream. For example, bulk proglacial meltwater analysis showed the increasing efficiency of a channelised system at atmospheric pressure beneath Gangotri Glacier, Garhwal Himalaya, with greater meltwater inputs through the melt season (Pottakkal et al., 2014). This was also inferred from the increase in the net flux and size of subglacially-eroded suspended particles through the melt season, as the drainage system became progressively more efficient and interconnected (Haritashya et al., 2010). Dye tracing experiments at Dokriani Glacier indicated a transition from distributed to channelised drainage through the melt season (Hasnain et al., 2001). On a diurnal scale, Kumar et al. (2009) found that the total ion concentration of proglacial meltwater at Gangotri Glacier increased from the afternoon onwards, interpreted as an enhanced subglacial component due to the englacial system developing through the day and transporting a greater proportion of supraglacial meltwater to the solute-rich glacier bed. Finally, substantial subglacial meltwater storage at debris-covered Lirung Glacier was inferred from its lower diurnal discharge variability relative to nearby debris-free Khimsung Glacier, Nepal Himalaya (Wilson et al., 2016).

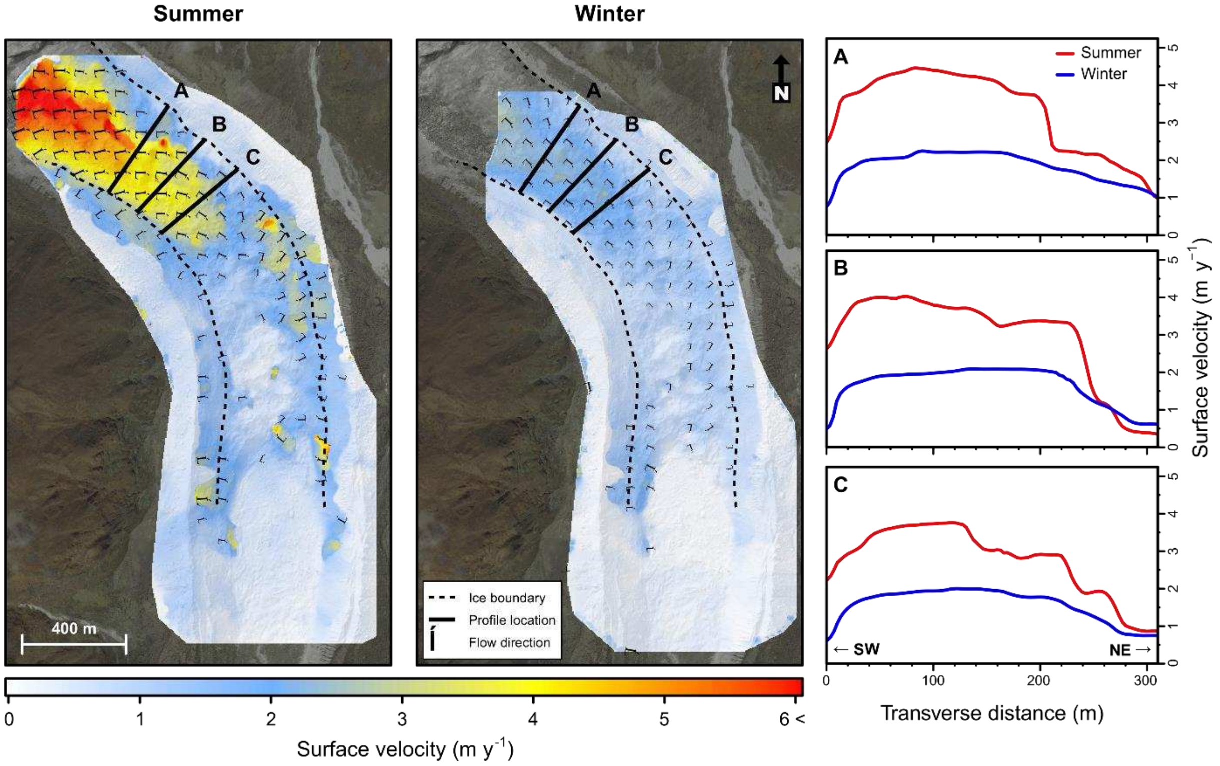

*Figure 8 – Surface velocity maps of Lirung Glacier, Nepal Himalaya, during summer (left) and winter (right), with three transverse velocity profiles **(A-C)** at the locations marked, from Kraaijenbrink et al. (2016b) available under a Creative Commons Attribution 4.0 License.*

4.2 Subglacial knowledge gaps

Very little is known about the subglacial drainage of High Mountain Asian debris-covered glaciers, largely due to the difficulty in accessing these systems. Furthermore, many debris-covered glaciers in High Mountain Asia terminate in lakes (Section 5.1.1), which increases the likelihood of some form of subglacial drainage system but reduces the likelihood of that system being channelised. Such lakes also severely hamper direct access to any outflow channels that might be present. Assuming the existence of such channels, it is entirely unknown whether subglacial networks flow directly into proglacial ponds at the bed, are routed to the surface upglacier and flow in supraglacially (similar to the pathway of some englacial drainage at Ngozumpa Glacier (Benn et al., 2017)), or are partially/wholly lost to groundwater. Additionally, the existence of base-level englacial streams and a perched water table are highly likely to complicate the detection of, and distinction between, englacial and subglacial systems, at least approaching the terminus. For example, towards the terminus of Khumbu Glacier, it has been inferred that the high local base-level results in the uprouting of the subglacial/deep englacial drainage system to the surface, yet, as the ice here is temperate, some meltwater would nonetheless be expected at the bed (K. E. Miles et al., 2018; Miles et al., 2019). However, basal ice temperatures and conditions for almost all other High Mountain Asian debris-covered glaciers are entirely unknown.

Transitions between the englacial and subglacial system are important to understand, as are discovering and tracking lost meltwater components – lost potentially to groundwater, to short- or long-term storage within the glacier, or to evaporation from the terminal moraine. The influence of the supraglacial debris cover on subglacial systems should also be addressed, if extensive subglacial drainage environments are discovered.

5. Proglacial hydrology

5.1 Proglacial zone

5.1.1 Proglacial lakes

One of the most distinctive characteristics of the proglacial zone of High Mountain Asian debris-covered glaciers is the frequent presence of a proglacial lake (Figure 9), which are far less common at equivalent clean-ice glaciers. These lakes form by a continuation of the processes of glacier thinning and supraglacial pond growth (Section 2.1.2) facilitated by the deposition of sufficient debris by debris-covered glaciers to create high, arcuate terminal moraines. Here, perched supraglacial ponds expand both downwards, eventually cutting to base-level, and laterally, often eventually coalescing to produce one large lake above and over the terminus (Basnett et al., 2013; Kattelmann, 2003; Mertes et al., 2016; Röhl, 2008; Watanabe et al., 2009). Although less common, base-level lakes that penetrate the full glacier thickness can form farther upglacier and expand downglacier through stagnant terminus ice, for example Imja Tsho on Imja Glacier, Nepal Himalaya (Figure 9) (Watanabe et al., 2009). The exact location of such a proglacial lake may be determined by the location of shallow englacial conduits that provide pre-existing lines of weakness as the perched ponds grow (Benn et al., 2017; Thompson et al., 2012). Proglacial lakes will therefore determine the hydrological base-level of the glacier, and are often dammed by the terminal moraine (Thompson et al., 2012).

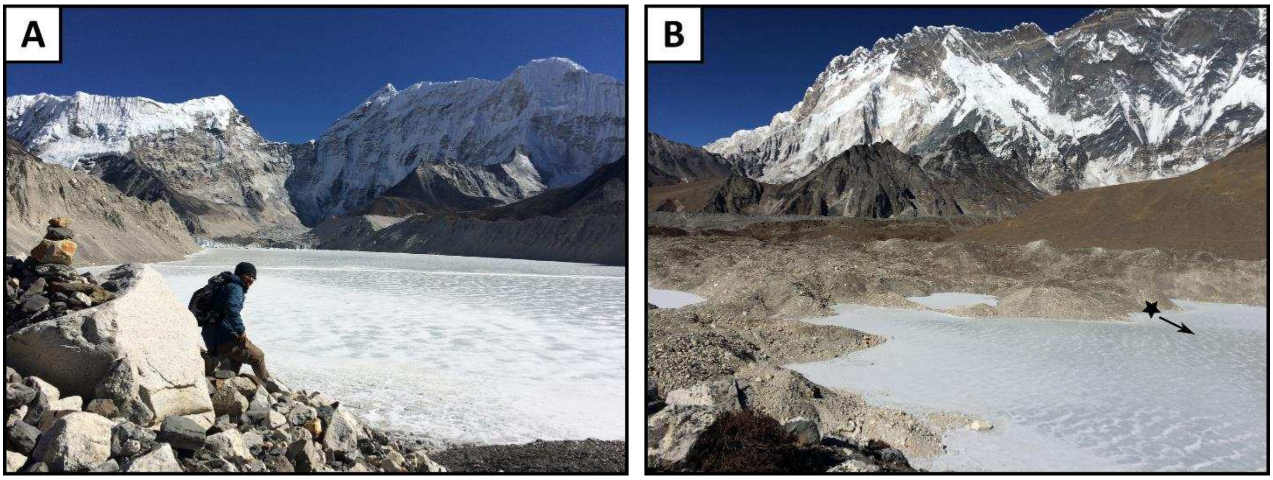

Figure 9 – Proglacial lake (Imja Tsho) with a frozen and snow-covered surface at Imja Glacier, Nepal Himalaya. ***A)*** *full length of Imja Tsho (~2.7 km in October 2018), looking upstream towards the calving front of Imja Glacier.* ***B)*** *detached (stagnant) glacier ice that dams the lake. The black star and arrow in B) show the location and direction A) was taken in.*

The formation of moraine-dammed proglacial lakes represents a final stage in the surface lowering and overall mass loss of debris-covered glaciers. Benn et al. (2012) defined three stages in the development of debris-covered glaciers: in regime one, all parts of the glacier are dynamically active; in regime two, surface lowering has begun and ice velocities decrease; in regime three, glaciers are completely stagnant and rapid recession may occur. The formation of a base-level lake indicates that a glacier has entered this third regime, and rapid recession may then occur through further expansion of that proglacial lake (Benn et al., 2012). An increasing number of proglacial lakes of increasing size have been observed in recent decades across the Hindu Kush Himalaya (Gardelle et al., 2011; Haritashya et al., 2018b; Thompson et al., 2012). The pattern of proglacial lake formation varies across the region, with glacial lake area in the western Himalaya decreasing 30–50% from 1990–2009 compared to an increase of 20–65% towards the east, where lakes are already more prevalent (Gardelle et al., 2011; Maharjan et al., 2018). This pattern at least partly reflects greater glacier recession in the west over this period (Gardelle et al., 2011).

Proglacial lakes continue to expand through similar mechanisms to supraglacial ponds (Section 2.1.2 above) until they are limited by substrate, enhancing glacial mass loss and thus meltwater production where the lake is underlain or dammed by ice (Carrivick and Tweed, 2013; Röhl, 2008). Initial growth occurs through subaqueous melting and subaerial ice-face melting, causing both deepening and lateral expansion. However, once triggered, calving becomes the dominant method of subsequent lake growth (Röhl, 2008; Thompson et al., 2012). Calving into a proglacial lake progresses from notch development and roof collapse to large-scale, full-height slab calving enabled by the lake deepening to the glacier bed (Kirkbride and Warren, 1997; Thompson et al., 2012). The water depth may then be sufficient to trigger extending flow in the now-unsupported ice cliff, increasing flow velocities and weakening the ice through crevasse formation and dynamically-induced thinning (Kirkbride and Warren, 1999; Thompson et al., 2012; Tsutaki et al., 2019). This can result in rapid and potentially unstable calving, substantially increasing glacier mass loss, as has been observed during several kilometres of such retreat at

Tasman Glacier, New Zealand (Kirkbride and Warren, 1999) and modelled for lake- and land-terminating glaciers in the Bhutan Himalaya (Tsutaki et al., 2019). Upglacier expansion of the lake (Watanabe et al., 2009) may have implications for the glacier's drainage system, such as by earlier interruption of meltwater routing (Carrivick and Tweed, 2013).

Very large proglacial lakes can alter a glacier's microclimate due to a lake's lower albedo and higher thermal heat capacity relative to the surrounding ice and soil, producing locally cooler summer air temperatures and warmer autumn temperatures (Carrivick and Tweed, 2013). This can slow local summer ice ablation and consequently reduce the amount of meltwater being produced and transported through the glacier, with implications for the development of englacial and subglacial drainage systems. If a moraine-dammed proglacial lake is present then the overwhelming majority of water transported through a debris-covered glacier is likely to pass through it (Benn et al., 2017). This has implications for drainage through the glacier and for the potential occurrence of glacial lake outburst floods (GLOFs).

5.1.2 Proglacial streams

Proglacial runoff from debris-covered glaciers can form a significant proportion of the discharge of large rivers downstream, particularly in High Mountain Asia: the Indus, Dudh Koshi, Ganges and Brahmaputra rivers all stem from glacial meltwaters (Pritchard, 2019; Ragettli et al., 2015; Wilson et al., 2016). In particular, glacial runoff buffers both seasonal (Bolch et al., 2019; Pritchard, 2019) and annual (Pohl et al., 2017) water shortages. Loss of glacier volumes due to longer, warmer melt seasons and decreased snow accumulation could result in much reduced water availability, greatly influencing downstream communities and ecology (Bolch et al., 2019; Pohl et al., 2017; Pritchard, 2019).

Proglacial discharge measurements, estimates and models have been run across High Mountain Asia, such as on individual glaciers in Nepal (Braun et al., 1993; Fujita and Sakai, 2014; Ragettli et al., 2015; Rana et al., 1997; Savéan et al., 2015; Soncini et al., 2016; Tangborn and Rana, 2000), Tibet (Kehrwald et al., 2008), the Tien Shan (Caiping and Yongjian, 2009; Han et al., 2010; Sorg et al., 2012), India (Hasnain, 1999, 1996; Khan et al., 2017; Singh et al., 2005, 1995; Singh and Bengtsson, 2004; Thayyen and Gergan, 2010), and for multiple catchments and entire regions (Winiger et al., 2005). However, of the studies listed above, five measured discharge for a year or less; three have 2–3 years of measurements; and only one has 6 years of measurements; the rest use modelling to obtain estimates of proglacial discharge.

The presence of surface debris can have a notable effect on the proglacial discharge of a debris-covered glacier, resulting in a proglacial hydrograph that is different from that of a clean-ice glacier. While no such comparison has been made for a High Mountain Asian debris-covered glacier, an example is shown from the debris-covered Dome Glacier, Canadian Rockies (Figure 10) (Mattson, 2000). Here, discharge was muted both diurnally and through the ablation season compared to the neighbouring clean-ice Athabasca Glacier (Figure 10), producing an annual variance in volumetric discharge of 1% compared to 24%, respectively. This is due partly to the suppression of surface melt by a debris cover (Section 2.1.1), and partly to the lags that are induced as a result of the debris layer – the additional time to conduct heat through the debris and the warmer local air temperatures due to the warming debris introduces a delay. Thus, peak melt can occur up to several hours after the maximum radiation receipt at the debris surface (Carenzo et al., 2016; Conway and Rasmussen, 2000; Evatt et al., 2015), and exceptionally recorded as being up to 24 hours later for debris layers > 0.85 m thick (Fyffe et al., 2014). This lag in diurnal peak melt is thus reflected in the timing of the highest stream flow, producing a later and less pronounced peak in the diurnal pattern of a debris-covered glacier's proglacial stream (Fyffe et al., 2019a, 2014).

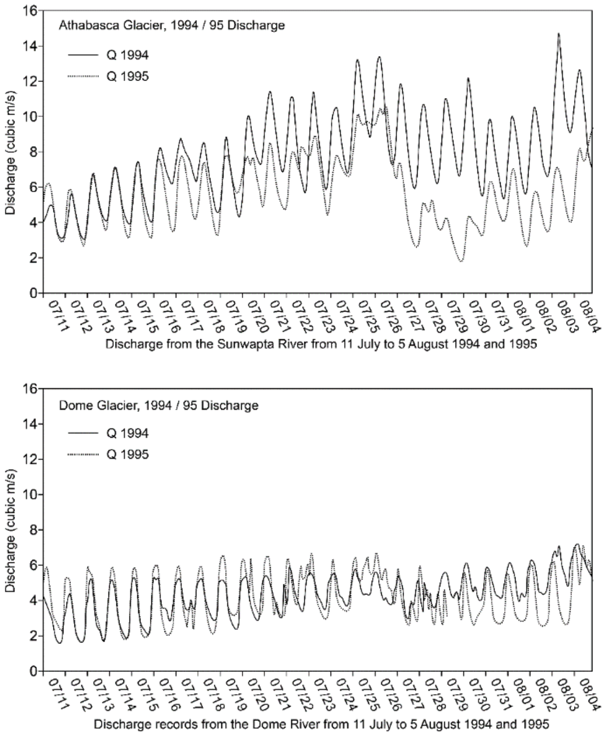

Figure 10 – Hydrographs of proglacial discharge of the clean-ice Athabasca Glacier and the adjacent debris-covered Dome Glacier, Canadian Rockies, over the ablation months of July and August 1994 and 1995. Figure redrawn from Mattson (2000).

Lags in proglacial discharge from debris-covered glaciers may also be caused by the temporary storage of water within the surface debris layer, for example, during rainfall events. This may influence subglacial and proglacial discharge by delaying and buffering water transfer at the surface, potentially affecting basal water pressures and minimising peaks in proglacial discharge (Brock et al., 2010). However, in the Himalaya, the monsoon precipitation is thought to exert only a weak control on the proglacial discharge hydrograph of glaciers unless the intensity is > ~20 mm d^{-1}, which occurred on 20% of rainfall days during four years of monsoon measurements on Dokriani Glacier (Thayyen et al., 2005). Early in the melt season, meltwater is also stored within the snowpack of debris-covered glaciers, providing a further delay in the transport of meltwater from the surface into the subsurface drainage system (Singh et al., 2006b). However, in the last two decades the amount of snowfall accumulation has decreased across the Himalaya, and is projected to decrease a further 20–40% by 2100 (Salerno et al., 2015; Viste and Sorteberg, 2015) which is likely to reduce this buffer and influence the future proglacial hydrograph pattern of debris-covered glaciers.

Groundwater storage within high-elevation glacial catchments has been inferred to interact with proglacial (and subglacial) stream networks, affecting the discharge patterns of the streams due to additional water storage and subsequent release (Gremaud et al., 2009; Smart, 1996, 1988). For example, a ~45 day lag between precipitation and discharge was observed for 12 glacierised and non-glacierised Himalayan catchments, indicating storage of up to two-thirds of the river discharge in a groundwater aquifer system before the monsoon, greatly affecting the annual discharge pattern (Andermann et al., 2012c). This has similarly been shown in much lower river suspended sediment concentrations measured post-monsoon, having been diluted as groundwater begins to be released (Andermann et al., 2012b, 2012a). Comparable processes may occur beneath the glaciers themselves, for example, at Khumbu Glacier in the pre-monsoon season, where more meltwater entered the glacier’s subsurface drainage system than exited the glacier at the terminus (Miles et al., 2019). Indeed, in the Jade Dragon Snow Mountain region of southwest China, 29% of the glacier meltwater was calculated to be stored in a karst aquifer (Zeng et al., 2015). Groundwater sinks of subglacial meltwater can therefore comprise a significant portion of the total glacial output, potentially resulting in underestimation of glacial ablation.

A range of models has been used to predict future runoff from debris-covered glaciers using various future climatic scenarios for a single glacier basin (Ragettli et al., 2015; Singh et al., 2008, 2006a; Zhang et al., 2007), and multiple glacier basins (Immerzeel et al., 2012; Lowe and Collins, 2001) up to a regional scale (Rees and Collins, 2006; Shea and Immerzeel, 2016). Currently, a large proportion of debris-covered glaciers worldwide, particularly in the Himalaya, have negative mass balances (Bolch et al., 2012, 2011; Kääb et al., 2012; Scherler et al., 2011). A recently observed decline in Himalayan snowfall will contribute further to the decreasing mass of these glaciers by both reducing accumulation rates and exposing the glacier surface to atmospheric melting earlier in the melt season (Salerno et al., 2015). Glacier contributions to catchment discharge in many regions have been predicted to increase over the next few decades, but as the glaciers continue to shrink, peak water will be surpassed and this proportion will begin to reduce substantially due to the significantly smaller volume of remaining glaciers (Barnett et al., 2005; Bolch, 2017; Bolch et al., 2012; Huss, 2011; Huss and Hock, 2018; Lutz et al., 2014). Shea and Immerzeel (2016) estimated that most basins will have declining glacier contributions to streamflow by 2100, and water shortage may then be a concern for many populated areas in the Karakoram, while reduced peak flows may represent a greater concern in the eastern Himalaya.

5.2 Proglacial knowledge gaps

Few glacial discharge monitoring stations have been in place for longer than a decade in High Mountain Asia, leaving current and future discharge volumes unknown for most debris-covered glaciers. The volume of potential glacial meltwater losses to groundwater, and whether these re-join the glacial system (subglacially, proglacially or further downstream), are also poorly understood.

Changes in proglacial hydrology are hampered by the absence of predictions of the future geometric development of High Mountain Asian debris-covered glaciers. For example, if surface lowering remains the dominant response to climate warming, glaciers may melt entirely and/or form large proglacial lakes that then dominate mass loss processes. Conversely, the inverted mass balance regime could result in a separation of the stagnant, heavily debris-covered lower glacier from the upper, less debris-covered regions, potentially providing ideal conditions for a base-level lake to form in between, dammed by the detached debris-covered ice.

6. Conclusions and future research priorities

The previous sections have outlined the state of knowledge and remaining knowledge gaps regarding the hydrological systems of debris-covered glaciers in High Mountain Asia. Based on this review, we conclude by proposing six hydrological research areas that we consider to be key priorities for future work. As the relative importance of each of these knowledge gaps also remains unknown, data collection should prioritise those parameters most inhibiting robust predictions of changes in glacier dynamics, geometry, mass balance and future water supply. It is also worth noting that a recurring theme spanning all of these topics and all parts of the hydrological system is the general lack of data available to characterise seasonal variations in flow routing and discharge. This is perhaps most relevant in the central and eastern parts of High Mountain Asia where the influence of the monsoon is strong; measurements during this time period would therefore be particularly valuable.

I. Elucidating glacier-wide water balance

Given the importance of glaciers as a source of water in high mountain regions, the robust quantification of water inputs into, and outputs from, the glacier system is paramount. Detailed hydrological field observations are required, both temporally and spatially extensive, to better constrain numerical model parameterisations. Water inputs should be simulated and examined independently of glacier-fed river discharge, with attention to process parameterisation to facilitate improvements in efforts to close the water balance. Water storage is also an important component of the water balance, discussed further in research priority IV below.

The limited measurement to date of precipitation across High Mountain Asia, particularly snow and rainfall partitioning, synoptic and seasonal-to-annual variations in precipitation gradients and rainfall fraction, should be assessed by establishing a network of robust automatic weather stations over a range of surface types and elevations. Glacier surface elevation change should be measured simultaneously by, for example, ultrasonic rangers to allow for melt and mass balance model calibration and validation. Precipitation gradients could be further addressed with dedicated accumulation measurements.

The temporary but long-term ‘loss’ of meltwater within the system, particularly the refreezing of meltwater within firn in the accumulation area but also refreezing within crevasses or the body of the glacier, requires better characterisation. Empirical data collected from snow pits and shallow ice cores would be sufficient to quantify these ‘losses’ over short timescales, complemented by longer-term records derived from deeper coring or visual examination of layering present in borehole walls. In the accumulation area, these methods would provide the additional bonus of historical records of local accumulation.

Accurate assessment of the amount of water lost through evaporation and sublimation can only be made through detailed examination of eddy covariance systems coupled with detailed meteorological observations. Future research should examine these processes not only from snow-covered areas, recently shown to be a key source of water loss (Stigter et al., 2018), but also over the accumulation and debris-covered ablation areas and the terminal and lower lateral moraines, which may equally contribute to evaporation and sublimation losses. Quantifying these moisture fluxes may be possible either by direct field measurement or by remote sensing for longer timescales.

Other priorities include quantifying losses to groundwater and better evaluating the role of debris in driving the observed hysteretic behaviour of downstream annual hydrographs. Isotopic analyses may shed light on water sources and variations therein, while catchment-scale dye or gas tracing studies tied closely to continuous measurements of discharge at various locations on and beyond the glacier could help to address the volumes of water delivered to groundwater systems (and if so, the proportion that re-joins the proglacial stream further downvalley).

II. Understanding hydrological processes influencing glacier mass balance

The efficiency of rainfall and meltwater routing from higher elevation locations should be evaluated due to its potential impact on glacier accumulation and mass balance by englacial melting. More detailed assessments of specific loci of storage or release and their timescales should be determined through direct field-based monitoring, perhaps allied to experimentation and melt model development.

Heat fluxes driven by meltwater conveyance to the englacial and subglacial environments of debris-covered glaciers (i.e. cryo-hydrologic warming (Phillips et al., 2010)), could be explored using numerical models guided by field-based measurements of supraglacial water fluxes and temperatures, along with borehole-based investigations of englacial temperature fields. Similarly, vertical heat transfer from warm supraglacial pond water to pond basins deserves attention. Pond expansion rates are partially controlled by the thermal conductivity and thickness of bottom sediments, necessitating measurements of temperature profiles and sediment cores, respectively. Future investigations may find value in focusing on systematic field-based bathymetry, pond coring and measurements of pond water and basal sediment temperatures at multiple depths, perhaps combined with the development of numerical models of heat transfer by such mechanisms.

There is a need for accurate knowledge of spatial variations in surface debris thicknesses and the influence of meltwater at the ice-debris interface, while models need to be able to simulate vapour fluxes through the debris. Thus, meteorological stations are needed to measure water content or relative humidity. Debris thickness maps and the existence of water could be reconstructed by refining algorithms from remotely-sensed data (both thermal imagery and surface lowering) or on the basis of field measurements by hand and/or high-frequency ground-penetrating radar.

Improved understanding of meltwater routing, particularly supraglacial and englacial drainage pathways, is necessary due to their strong association with the formation of supraglacial ice cliffs, which account for disproportionate amounts of surface melt. Investigations should map current stream coverage and changes in surface topography and hydrology (for example, the collapse and surface exposure of shallow englacial systems), either in the field or remotely using satellite images where streams are large enough, supplemented by methods such as dye tracing for shallow englacial systems beneath the surface.

III. Identifying the influence of drainage and meltwater storage on ice motion

Meltwater presence at the bed or the terminus of debris-covered glaciers can affect the velocity of both land- and lake-terminating glaciers. A better understanding and inclusion of subglacial hydrological processes into models of glacier dynamics will improve future simulations of ice flow and glacier evolution. Within subglacial hydrological processes, better quantification is needed of the inputs to the system (i.e. coupling meteorological data with melt modelling), the volume of water present at the bed (for example, by monitoring subglacial water pressure in deep borehole arrays) and the volumes of water lost from the system (i.e. by calculating the glacier's water balance).

Ice motion should be separated into its constituent components (i.e. ice deformation and basal sliding), with particular focus on measurements acquired during the melt season and on an individual glacier scale. A recent study argued on the basis of remote sensing that basal water pressure, and consequently sliding, is necessary to model seasonal and inter-glacier variability accurately (Dehecq et al., 2019). Therefore, glacier surface velocities should be measured, for example through field-based GPS or remote sensing studies. The recently available and constantly growing archive of rapid-repeat, high-resolution optical and radar remotely-sensed imagery will help future work to improve knowledge of seasonal velocities. Deeper ice velocities and strain can be recorded within boreholes, ideally to the glacier bed. Such boreholes can also allow measurements of the glacier thermal regime and bed substrate, while improved mapping of glacier bed topography across High Mountain Asia is necessary to constrain ice thicknesses. Finally, in order to assess the influence of calving from a proglacial lake, the above measurements should be collected in comparative studies between lake- and land-terminating High Mountain Asian glaciers.

IV. Characterising seasonal changes in hydrology

Targeted research is needed to measure seasonal changes in the hydrological storage components absent from clean-ice glaciers, the improved understanding of which is needed to represent the drainage system of debris-covered glaciers appropriately in hydrological models. For example, seasonal changes in the area and volume of perched supraglacial ponds could be achieved at the glacier scale using rapid-repeat optical satellite imagery to maximise likelihood of observation and/or by leveraging fine-resolution synthetic aperture radar satellite data, which is insensitive to cloud cover. Improved process-based understanding should also be made with detailed field-based studies. Inferences of seasonal storage and release from subsurface reservoirs exist, but the processes and timescales on which these occur require quantification.

Detailed examination of debris water content (including the seasonal thaw dynamics of the debris layer, influencing the debris hydraulic transmissivity) can be made using soil moisture sensors at depth intervals, while through-debris transmissivity and snowpack storage/release could be assessed with dye tracing experiments. These processes will aide better understanding of the role of debris, snow and firn in transmitting meltwater to supraglacial streams and beyond.

Glacier drainage systems respond dynamically to the seasonal production of meltwater; this is manifest at clean-ice glaciers when snowline retreat stimulates the progressive upglacier transition from inefficient to efficient drainage. Research is needed at High Mountain Asian debris-covered glaciers to evaluate the distinctive seasonal dynamics due to the additional storage components and distinct melt generation patterns, for example, through dye tracing, glaciospeleology or bulk proglacial meltwater analysis. Such studies would also aide a better general understanding of the nature and form of englacial and subglacial drainage.

Finally, the seasonal structure and dynamics of debris-covered glacier hydrological systems must be understood in the context of melt and discharge. An integrated effort to assess seasonal changes in debris-covered glacier hydrology should be coupled with melt season meteorological and ablation measurements, as well as development of a continuous discharge record through proglacial discharge monitoring stations.

V. Evaluating hydrological hazards

The growth in both number and size of supraglacial ponds is one of the clearest visual signs of debris-covered glacier decay. Research should focus on predicting future lake locations and the timing of formation, possibly through modelling by identifying overdeepenings. Moraine-impounded sites (such as where base-level terminal lakes have been observed to develop) are more complex – investigations into the drainage capability (evidence of free-drainage as opposed to impoundment) combined with remotely-sensed observations of expanding, coalescing supraglacial pond chains may provide a suitable starting point. Improved understanding of supraglacial pond expansion rates, discussed in research priority II, is also crucial, while accurately modelling the longevity of ice cliffs could be improved with high-resolution DEMs (obtained, for example, through Structure-from-Motion) coupled with simple numerical modelling.

Assessments of how ‘dangerous’ a lake is (potential of a catastrophic GLOF occurring) often disagree (e.g. Haritashya et al., 2018a; Maharjan et al., 2018; Rounce et al., 2016), and recent events such as the 2015 Gorkha earthquake suggest that many glacial lakes may be more stable than hitherto considered. Misconceptions still exist within these studies, with many assuming the lake area and rate of lake expansion to be critical to the hazard level, while in practice, a large number of factors likely contribute, many of which may be specific to each glacial lake. Traditional magnitude-frequency relationships are no longer relevant as the current state of mountain environments is beyond historic precedence. Therefore, alternative forms of event prediction are needed, such as site-specific scenario development depending on different event magnitudes.

Field-based measurements should be made on an individual glacial lake basis and the downstream area in order to determine the potential hazard and risk of a GLOF. Knowledge of moraine dam composition (including sediment type and the presence or absence of an ice core) and the existence of seepage or piping is needed, and could be addressed by radar, seismics, drilling or coring into moraines to characterise soil strength and composition. Flood hydrographs could be better constrained by geotechnical modelling to understand dam failure mechanisms. While predicting the timing of an outburst flood is near impossible, particularly those originating from englacial and subglacial sources, characterising subsurface drainage and routing and seasonal release of stored water may help to identify likely timing and locations of sudden outbursts (research priority IV). Cascading hydrological hazards should also be addressed, which may be triggered by very high-elevation and often hanging glaciers that are seldom studied. The thermal conditions and hydrology of these glaciers should be investigated, for example, by hot-water drilling and installing temperature sensors, along with dye tracing and discharge monitoring.

VI. Predicting future hydrological changes over short and long timescales

Understanding the timescales over which debris-covered glaciers will lose mass, thus influencing the amount of meltwater generated and subsequent hydrological processes, depends on developing a new generation of glacier models that capture both the complex properties of debris transport by ice and the key processes affecting sub-debris mass balance. Numerical model predictions need to integrate opposing processes on different scales, for example, encompassing the glacier-scale ‘debris-cover anomaly’ (recently observed, but unexplained, debris-covered glacier mass loss rates that are similar to those of clean-ice glaciers (Gardelle et al., 2012; Pellicciotti et al., 2015)) whilst maintaining the overall insulation effect of the debris-covered area. Additionally, the relationship between debris transport, ice flow and mass balance is an important feedback that needs to be included in glacier models to predict debris-covered glacier change over timescales longer than a few decades (Rowan et al., 2015).

Field and remote sensing data are required at the correct scale and resolution for numerical models to evaluate their output and provide accurate predictions of glacier mass change. Subsequently, these observations of mass balance and ice flow processes need to be parameterised to allow simulations of regional glacier change that do not neglect the influence of important small-scale processes, and that also contain enough process-based understanding to predict how these controls will evolve over time. Understanding the importance of local-scale processes for the long-term evolution of debris-covered glaciers compared to climatic controls on glacier mass and dynamics is crucial.

As debris-covered glaciers shrink, primarily by surface lowering, the debris cover will thicken and increase insulation, reducing ablation over a potentially greater area of the terminus. Debris-covered glaciers are therefore already larger and likely to decline slower than equivalent clean-ice glaciers in the same climatic regime; as a result, their meltwater will temporarily become a relatively larger component of the annual hydrological budget as clean-ice glaciers vanish first over the next two centuries. Accurate dynamic glacier models are therefore needed to predict changing hydrographs and contributions to downstream water supplies, particularly after peak water has passed. Supraglacial ponds play an important role in modulating the proglacial hydrograph and, in the long-term, may provide a natural water supply reservoir during periods of drought. However, sedimentation rates within ponds, and therefore their likely longevity, should be quantified by hydrological stations both within and at the outlet of larger ponds.

The acceleration of debris-covered glacier mass loss and decrease in glacial runoff as peak water passes may lead to proglacial streams becoming proportionately more sediment-laden. This may be enhanced during the melt season, particularly in regions of High Mountain Asia affected by heavy monsoon rains which can enhance supraglacial debris weathering (Collins, 1999). In addition, the ice within larger debris-covered glaciers is older than in smaller glaciers and will thus contain a longer legacy of environmental contaminants. Ultimately, this may result in higher volumes of sediment and potentially pollutants being released through the proglacial stream into water supplies, particularly during the melt season. Discharge and water quality should therefore be monitored with hydrological monitoring stations on proglacial streams across High Mountain Asia. Combined with modelling efforts and improved hydrological understanding, this will allow mitigation strategies to be planned for the vast downstream populations that depend on glacial meltwater.

7. Author contributions

KM and BH planned the manuscript. KM led the manuscript writing and illustration. All authors contributed to the writing and editing of the manuscript.

8. Competing interests

The authors declare that they have no conflict of interest.

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