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Supraglacial ponds regulate runoff from Himalayan debris-covered glaciers

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Key Points:

- The monsoon season runoff hydrograph from Khumbu Glacier displays progressive changes in diurnal timing and recession characteristics.
- We propose that observed hydrological behavior results from seasonal evolution of supraglacial ponds and connections.
- Predicted expansion of debris-covered areas and pond extents will influence downstream timing, availability and quality of meltwater in the Himalaya.

Abstract

Meltwater and runoff from glaciers in High Mountain Asia is a vital freshwater resource for one fifth of the Earth's population. Between 13% and 36% of the region's glacierized areas exhibit surface debris cover and associated supraglacial ponds whose hydrological buffering roles remain unconstrained. We present a high-resolution meltwater hydrograph from the extensively debris-covered Khumbu Glacier, Nepal, spanning a seven-month period in 2014. Supraglacial ponds and accompanying debris cover modulate proglacial discharge by acting as transient and evolving reservoirs. Diurnally, the supraglacial pond system may store >23% of observed mean daily discharge, with mean recession constants ranging from 31 to 108 hours. Given projections of increased debris-cover and supraglacial pond extent across High Mountain Asia, we conclude that runoff regimes may become progressively buffered by the presence of supraglacial reservoirs. Incorporation of these processes is critical to improve predictions of the region's freshwater resource availability and cascading environmental effects downstream.

1 Introduction

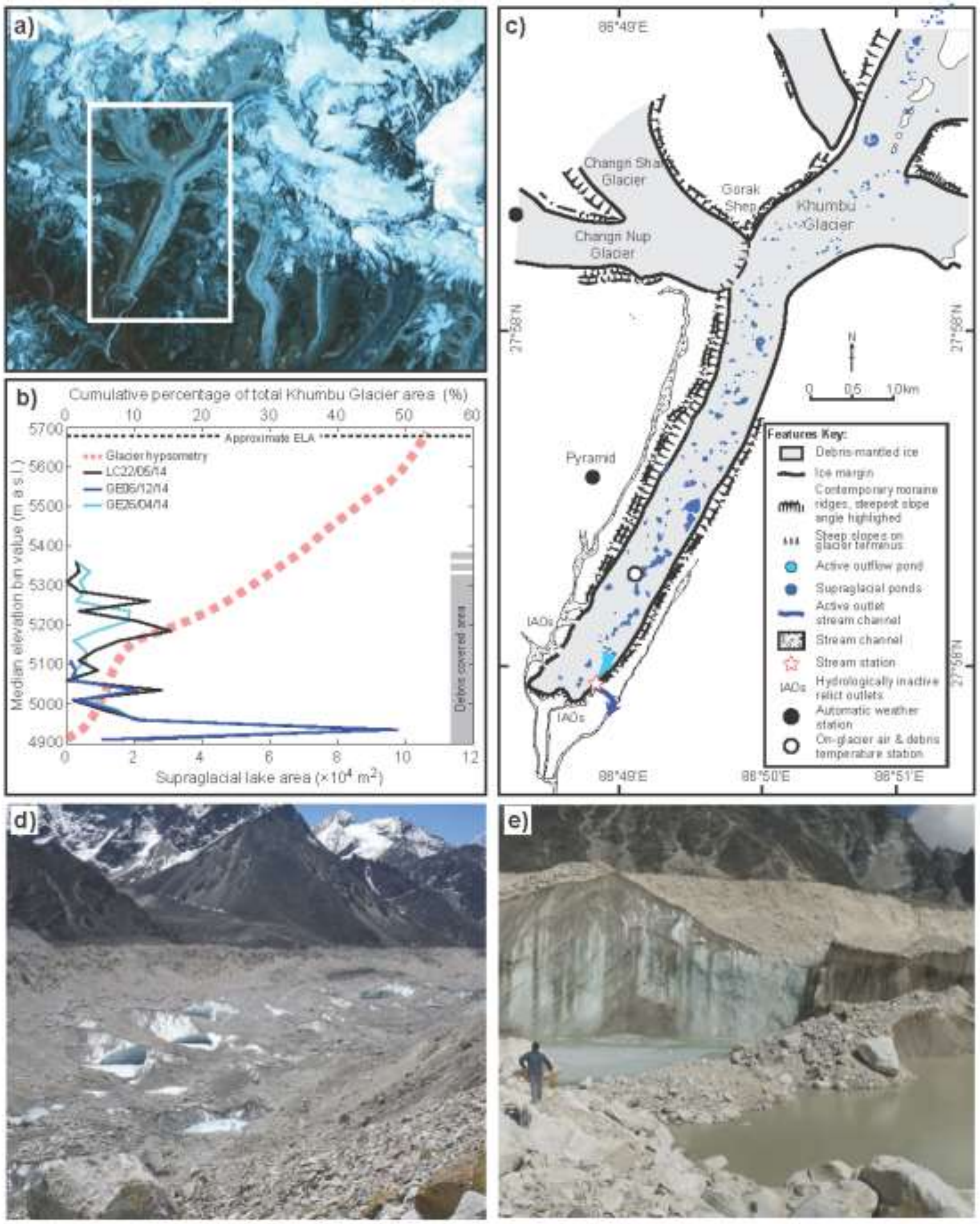
An estimated 1.4 billion people depend on freshwater sourced from snow and ice melt in High Mountain Asia [*Immerzeel et al*., 2010]. Although highly variable across the region, this meltwater typically contributes between 20% and 50% of the total annual runoff [*Bookhagen and Burbank,* 2010; *Immerzeel and Bierkens*, 2012; *Lutz et al*., 2014]. Contemporary observations [*Bolch et al*., 2012; *Kaab et al*., 2012; *Pritchard,* 2017; *Brun et al*., 2017] and predicted trends [e.g. *Shea et al*., 2015a; *Soncini et al*., 2016] of glaciers in the Himalaya demonstrate declining ice volumes, but highlight uncertainty over the associated glacio-hydrological impacts and consequent water stress arising from climate change. One important cause of this ambiguity is the presence of a supraglacial debris mantle present on many of the region's glaciers, which covers up to 36% of the glacierized area in the Everest region [*Bolch et al*., 2012; *Kaab et al*., 2012; *Scherler et al*., 2011; *Thakuri et al*., 2014]. This debris mantle commonly causes downglacier ablation areas to exhibit low surface gradients and velocities [e.g. *Quincey et al*. 2007; *Scherler et al*., 2011; *Thompson et al*., 2016; *Salerno et al.*, 2017] and its overall extent is increasing and predicted to expand further [*Rowan et al*., 2015; *Thakuri et al*., 2014; *Bolch et al*., 2008]. Supraglacial debris exerts a critical influence on glacier response to climate forcing because, dependent on its thickness, debris can either accelerate or retard ablation [*Østrem* 1959; *Evatt et al.,* 2015]. This effect, coupled with the dynamic topography of the glacier surface, promotes highly heterogenous ablation and the formation of surface lakes and ponds, which are a common feature of receding debris-covered glaciers [*Reynolds*, 2000; *Benn et al.*, 2012; *Gardelle et al*., 2011; *Watson et al*., 2016; *Bassnet et al*., 2013; *Miles et al*., 2016, 2017a,b; *Narama et al*., 2017]. However, the processes and causal relationships underpinning the spatial distribution of supraglacial ponds remain unclear [*Salerno et al.*, 2017].

Supraglacial ponds are 'hotspots' of glacier ablation [*Mertes et al*., 2016] due to their reflective and thermal characteristics [*Sakai et al*., 2000; *Benn et al*., 2001; *Miles et al*., 2016; *Watson et al.,* 2017a] and the presence of bare-ice cliffs associated with pond formation and growth [*Sakai et al*., 2002; *Brun et al.*, 2016; *Watson et al.*, 2017b]. Consequently, ponds may accelerate glacier thinning and recession and act as temporary meltwater storage reservoirs [*Benn et al*., 2001, 2012]. Ponds on debris-covered glaciers are commonly either transient features due to inception or collapse of near-surface or shallow englacial drainage routes and consequent drainage, or appear ‘perched’ in closed basins where efficient flowpaths are absent [*Reynolds*, 2000; *Benn et al*., 2001; *Miles et al*., 2017b; *Watson et al*., 2017a]. Seasonally, ponds on Himalayan glaciers typically grow both in area and depth [*Watson et al.,* 2017a], attaining maximum extent mid-monsoon and declining in size thereafter [*Miles et al*., 2017a; *Narama et al*., 2017; *Watson et al*., 2016]. Inter-annually, debris redistribution and change in surface topography results in variation in pond positions [*Narama et al*., 2017; *Watson et al*., 2016] and as ponds attain their local hydrological base-level they may evolve into larger scale lakes [*Thompson et al*., 2016; *Mertes et al*., 2016]. Observations of supraglacial pond water quality confirm that hydrological linkages do exist between ponds [*Takeuchi et al*., 2000; *Bhatt et al*., 2016], and pond extent may be governed by the evolving development and (re)organization of supraglacial drainage systems [*Watson et al*., 2016, 2017a; *Miles et al.*, 2017b]. Yet the extent to which these ponds impact upon meltwater generation and modify the seasonal hydrograph remains poorly quantified.

A lack of *in situ* observations of meltwater generation, transit and runoff for Himalayan glaciers [*Immerzeel et al*., 2012; *Bajracharya et al*., 2015] has led to uncertainties in the prediction of their hydrological response to environmental forcing. For example, some numerical models of debris-covered glacier systems utilize a linear reservoir parameterization linking proglacial discharge to meltwater production [e.g. *Ragettli et al*., 2015; *Fujita and Sakai*, 2014]. Such methods though fail to account for the potential hydrological complexities in the region. Specifically, the presence of interconnected supraglacial ponds implies a potentially complex hydrological system [*Miles et al.*, 2017b] that will modulate the water inputs to, and outputs from the glacier system. Hence, the acquisition of detailed measurements characterizing the hydrological behavior of debris-covered glaciers on diurnal to seasonal timescales is an imperative for improved predictions of meltwater delivery to downstream water resources throughout the Himalaya. Here, we present the results of a glacier-scale runoff monitoring program at the debris-covered Khumbu Glacier in the Everest region of Nepal. Our measurements span a 190-day period from April to November 2014 including the summer monsoon season.

2 Field Site and Methods

Khumbu Glacier (27.97°N, 86.83°E) flows from the southern flanks of Mount Everest to its terminus at ~4900 m a.s.l. (Figure 1a). The terminus elevation is slightly lower than the local permafrost limit of ~5000 m a.s.l. [*Schmid et al.*, 2015]. The glacier is likely to be polythermal, with an estimated 17 m deep cold surface ice layer [*Mae et al.*, 1975]. The glacier thinned at approximately –0.6 m a^{-1} between 2000 and 2015, with losses of –1.4 m a^{-1} at elevations of 5200–5300 m [*King et al.*, 2017]. Approximately 47% of the 41 km^2 glacier including the Changri Nup and Changri Shar tributaries is debris-covered (Figure 1b). Supraglacial debris thickness varies from 0.1 m to over 3 m and is concentrated over the lowermost 8 km of the glacier [*Soncini et al*., 2016], overlying 20 m to 440 m of glacier ice [*Gades et al*., 2000]. Recent observations [e.g. *Nuimura et al*., 2011] indicate that this debris cover has become increasingly topographically uneven: differential ablation has resulted in a complex glacier surface characterized by the presence of numerous supraglacial water bodies [*Wessels et al*., 2002; *Watson et al*., 2016]. Throughout 2014, ~1% of the total debris-covered area comprised supraglacial ponds (Figures 1b-e). However, as elsewhere in the region, the hydrological evolution and connectivity of these supraglacial ponds is poorly constrained. The Changri Nup and Changri Shar tributaries are now physically disconnected, but retain a surface hydrological connection with the Khumbu Glacier tongue [*Vincent et al*., 2016]. The only visible source of meltwater runoff flowing from the Khumbu catchment emerges from a turbid supraglacial lake situated close to the eastern glacier margin (Figure 1c). There is no evidence of alternative, active terminal or lateral outlets for englacial or subglacial drainage pathways. Runoff data were recorded immediately downstream of this outlet lake, where meltwater drains via a breach in the eastern Little Ice Age lateral moraine to the upper Dudh Koshi.



a)
b)
Cumulative percentage of total Khumbu Glacier area (%)
Approximate ELA
Glacier hypsometry
LC22/06/14
GE06/12/14
GE26/04/14
Median elevation bin value (m a.s.l.)
Debris covered area
Supraglacial lake area (×10⁴ m²)
c)
86°49'E
86°50'E
86°51'E
27°58'N
Changri Shar Glacier
Changri Nup Glacier
Gorak Shep
Khumbu Glacier
Pyramid
IAOs
0 0.5 1.0km
N
Features Key:
Debris-mantled ice
Ice margin
Contemporary moraine ridges, steepest slope angle highlighed
Steep slopes on glacier terminus
Active outflow pond
Supraglacial ponds
Active outlet stream channel
Stream channel
Stream station
Hydrologically inactive relict outlets
Automatic weather station
On-glacier air & debris temperature station
d)
e)

Figure 1: (a) ASTER imagery (Sept 2012) of the Everest region, Nepal, outlining lower elevations of the Khumbu Glacier detailed in (c); (b) hypsometry and supraglacial pond area in Khumbu Glacier ablation zone based on satellite imagery from 26 April, 22 May and 6 December 2014 [see *Watson et al.*, 2016]; (c) ablation zone of Khumbu Glacier highlighting key data collection sites and major geomorphological features, including hydrologically inactive outlets (IAOs) indicative of abandoned drainage routes and supraglacial lake positions on 26 April 2014 prior to the onset of the monsoon season; (d, e) oblique images illustrating typical debris cover and pond morphology, taken during the pre-monsoon period, May 2014.

Discharge (Q) data were collected between 14 May and 12 November (Day of Year (DOY) 135 to 317) using standard methods [*Herchy*, 1995]. A hydrological monitoring station was established in a stable reach of the sole outflow channel at 4930 m a.s.l.. Average water stage was recorded at 30 min intervals using a Druck PDCR1730 pressure transducer and Campbell Scientific (CS) CR1000 data logger. A stage-discharge rating curve was developed using triplicate dilutions [*Hudson and Fraser*, 2005] of 3 mL aliquots of 10% fluorescein and a Turner Designs Cyclops7 fluorometer linked to a CS CR10X datalogger. A non-linear stage-discharge relationship yielded a coefficient of determination of $r^2 = 0.79$ (n = 18). Estimated uncertainty in Q is <15%, although this is increased for higher Q values [see *Supplementary Information*; *Rantz et al.*, 1982; *Sakai et al.*, 1997; *DiBaldassarre and Montanari*, 2009]. On-glacier air temperature (T_a) and debris temperature (T_d) were monitored at 4935 m a.s.l. using Gemini TinyTag2 logging thermistors with a stated measurement accuracy of ±0.4°C (Figure 1c). The T_a sensor was mounted in a naturally aspirated radiation shield 1 m above the debris surface; the T_d sensors were located within the debris layer at depths of 0.55 and 1.0 m below the surface and away from the debris-ice interface. All temperature measurements were recorded at 30-min intervals. Local incident shortwave radiation (SW_{in}) was recorded at an automatic weather station 5363 m a.s.l. on the Changri Nup Glacier (Figure 1c) using a Kipp & Zonen CNR4 sensor with 3% uncertainty. Precipitation (P) was measured at Pyramid Observatory (Figure 1c) at 5035 m a.s.l. using a Geonor T-200 gauge; these hourly data were corrected for undercatch of solid precipitation and have an estimated accuracy of ±15% [*Sherpa et al.*, 2017].

We examined the timing of peak discharge and the shape of the diurnal hydrograph using standard approaches; lag times between time-series were identified using a moving window cross-correlation [e.g. *Jobard and Dzikowski*, 2006], while we classified diurnal hydrographs using a paired Principal Components Analysis (PCA) and Hierarchical Cluster Analysis (HCA) approach [e.g. *Hannah et al*., 2000; *Swift et al.*, 2005]. Specifically, daily (24 hr) hydrographs were assumed to commence at low Q at 06:00, PCA was conducted without rotation and only components with eigenvalues > 1.0 were retained. PCA identified modes of diurnal Q variation defined by the standardized component loadings and these loadings for each day were clustered using Euclidean distance measures and a within-groups linkage method. A total of 6 groups were identified and further classified using a second, independent HCA that defined diurnal hydrograph similarity based on key discharge metrics following z-score normalization. Daily hydrographs were then described based on 'shape' defined by PCA clusters and 'magnitude' identified in the secondary HCA.

Estimates of recession storage constants (K) for each diurnal hydrograph were derived from semi-logarithmic plots of Q versus time [e.g. *Gurnell*, 1993; *Hodgkins et al*., 2013] where:

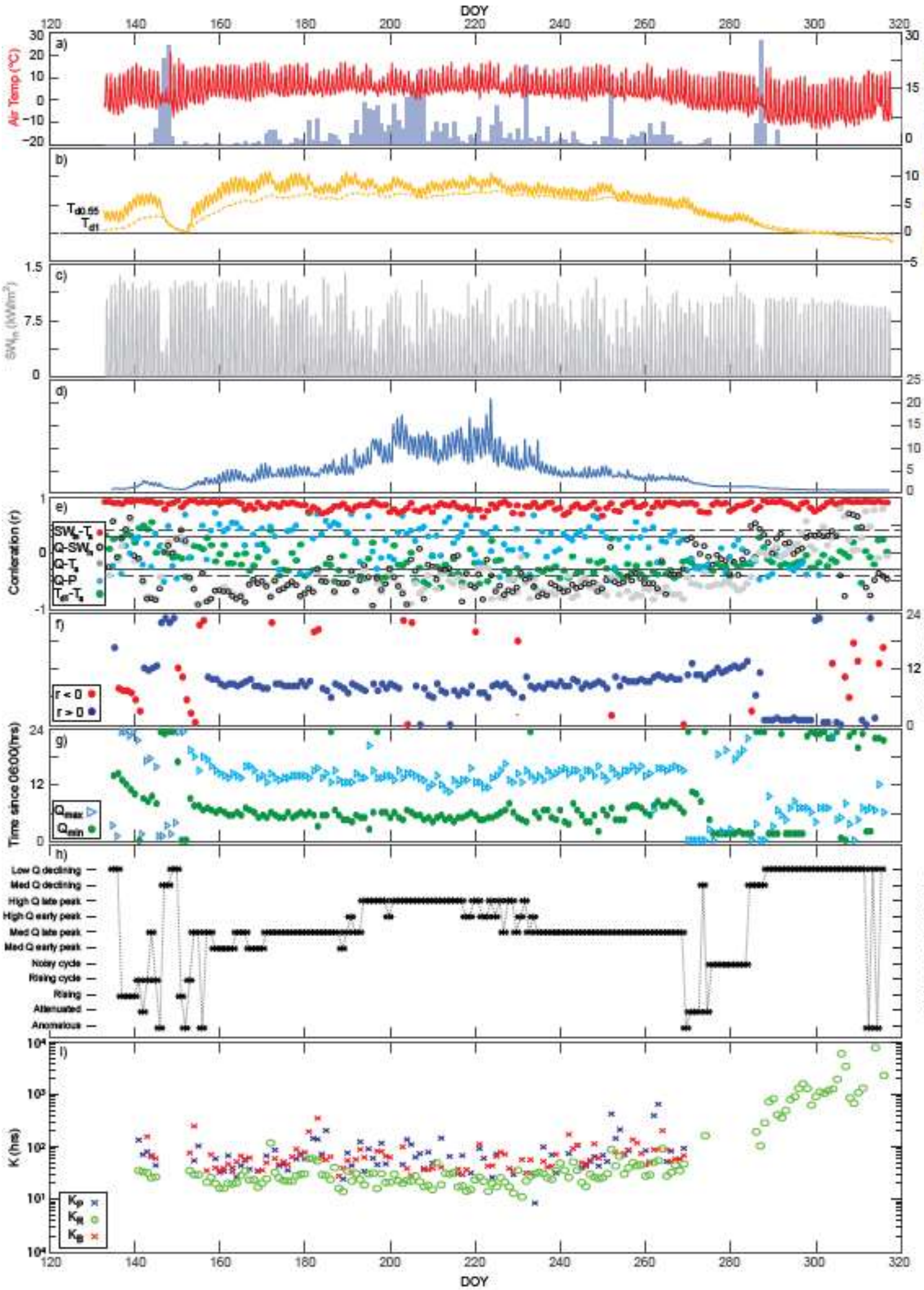
$$\mathbf{K} = \frac{-t}{\ln\left(\frac{Q_t}{Q_0}\right)} \qquad \text{Eq.1}$$

for which t is time since the start of the recession segment, and Q_0 and Q_t the discharge at the start of the recession segment and at time t, respectively. For all days classified as exhibiting diurnal discharge cycles (n = 117) or constant recessional hydrographs (n = 29), K-values were calculated from the time-step following peak discharge, or from 18:00 in the case of persistent recession hydrographs. Recession segments and associated aggregate recession constants were identified using segmented linear regression for cases exhibiting durations >1 hr.

3 Results

The meteorological and discharge time-series (Figure 2a-d) for the 2014 monsoon season reveal that T_a and SW_{in} exhibited strong diurnal variations, with highest incident energy fluxes between 10:00 and 15:00, as typifies the region [see *Shea et al*., 2015b]. These two variables were highly correlated over the diurnal cycle ($r > 0.5$, $p < 0.05$) throughout the observation period (Figure

2e). Seasonal changes in T_d aligned well with T_a, although at the daily timestep, correlation suggested a changing lag between variables (Figure 2e). Despite a distinct diurnal variability in T_d, variation was suppressed at depth (Figure 2b), and T_d remained below 0°C following DOY 300. The seasonal pattern of Q broadly followed that of T_a with an underlying diurnal fluctuation of between 0.005 and 12.3 m^3 s^{-1}, and daily mean Q peaking at ~9 m^3 s^{-1} which compares well with published records of discharge during 2014 for the upper Dudh Koshi [*Soncini et al*., 2016; see *Supplementary Information*]. Interestingly, diurnal correlation indicated Q and both T_a and SW_{in} vary out of phase for much of the observation period (Figure 2e). Q lagged T_a progressively decreasing from 12 to 6 hrs until DOY 220, and subsequently returning to lags >12 hrs until DOY 285 when lags dropped again to ~6 hrs (Figure 2f). The diurnal hydrograph cycle became steadily delayed until DOY270 when T_d declined to ~5°C and continued to fall when a protracted hydrograph recession dominated. While statistically significant diurnal correlations between Q and P were found, these were inconsistent and showed no systematic trend (Figure 2e). Lag analysis highlighted statistically significant correlations ($r > 0.405$, $p < 0.05$) between Q and P over 24 hr periods, predominantly with Q lagged by >10 hrs, however no pattern in lag time was observed.


DOY
a)
Air Temp (°C)
Precipitation (mm)
b)
$T_{d0.55}$
T_{d1}
Debris Temp (°C)
c)
SW_{in} (kW/m²)
d)
Q (m³/s)
e)
Correlation (r)
SW_{in}-T_a
Q-SW_{in}
Q-T_a
Q-P
T_{d1}-T_a
f)
r < 0
r > 0
Q lag time (hrs)
g)
Time since 06:00 (hrs)
Q_{max}
Q_{min}
h)
Low Q declining
Med Q declining
High Q late peak
High Q early peak
Med Q late peak
Med Q early peak
Noisy cycle
Rising cycle
Rising
Attenuated
Anomalous
Hydrograph classification
i)
K (hrs)
K_P
K_R
K_B
DOY

166

Figure 2: Time-series of (a) on-glacier air temperature T_a and total daily precipitation P, (b) debris temperature T_d at 0.55 and 1.0 m below the debris surface, (c) incident shortwave radiation SW_{in} and (d) meltwater discharge Q. Analyses identify (e) daily correlations between T_a, SW_{in}, P and Q with the 95% confidence levels indicated for the hourly ($r \approx 0.41$) and half-hourly ($r \approx 0.29$) data sets, (f) the lag time between daily peak T_a and maximum Q, (g) the timing of minimum and maximum Q, (h) the daily hydrograph classification based on shape and magnitude, and (i) the three principal hydrograph recession constants (K_P, K_R and K_B).

Three sequential recession segments were identified as typical within the time-series: (i) slow decrease in Q lasting ≤ 7 hours immediately following peak Q (K_P), (ii) major recession component of rapid decrease in Q over ~9 hours duration (K_R), and (iii) a second slow decrease for ~5 hours prior to the onset of the next diurnal cycle (K_B). Where only a singular extended recession was identified, this was taken to be K_R. K_P and K_B were found to be statistically similar, but lacked a significant temporal trend, while K_R showed a strong non-linear association with peak Q, decreasing and increasing as the monsoon season progressed. While aggregate K-values broadly agree with the magnitude of those identified in other glacial runoff records (mean K_P = 86.7 and K_B = 72.4 hrs, while mean K_R = 108 hrs for the season, but 31.1 hrs before DOY270), the recession segment pattern contrasts with the commonly reported systematic increase in K-values over diurnal hydrograph recession segments [e.g. *Gurnell*, 1993; *Hodgkins et al.*, 2013]. No association between K-values and P or daily peak Q was found. In tests, uncertainty related to the rating curve used to derive the Q time-series [see *Supplementary Information*; *Rantz et al.*, 1982] did not impact the recession patterns identified; however, if using a power-law rating curve [*Herchy*, 1995], recession constants K_P, K_R and K_B increased by 81±30%, 51±50% and 57±26% respectively.

4 Discussion

Our results from Khumbu Glacier indicate a hydrological configuration with both similarities and distinct differences to those typically reported for Alpine glacier systems in Europe and elsewhere. Systematic progression in timing of peak Q, seasonal undulation in diurnal discharge amplitude, diurnal hydrograph asymmetry, and clear patterns in hydrograph classification are commonly described for temperate, debris-free alpine glaciers [e.g. *Richards et al*., 1996; *Hannah et al*., 2000; *Swift et al*., 2005; *Jobard and Dzikowski*, 2006]. Typically, as the snowline recedes upglacier and melt season advances, peak Q occurs progressively closer to the time of heightened SW_{in} and T_a and, even for large south-facing valley glaciers such as Aletschgletscher, equivalent in size to Khumbu Glacier, Q lags the meteorological drivers of melt by <5 hrs during much of the ablation season [e.g. *Lang*, 1973; *Verbunt et al*., 2003]. As ablation continues on debris-free glaciers, the amplitude of Q increases, and the hydrograph form becomes more accentuated. Here, particularly prior to DOY230 (Figures 3f-h), the patterns of hydrograph characteristics resemble those reported for temperate alpine settings.

However, in contrast to debris-free alpine counterparts, the timing of daily peak and minimum discharge at Khumbu Glacier shows a more marked delay relative to meteorological drivers of ablation: peak Q occurs ≥6 hours after maximum SW_{in} and T_a, while minimum Q commonly coincides with peak irradiance. Q lagging energy fluxes reflects the delay in energy transfers that initiate melt, particularly for those associated with exchange at the atmosphere-debris interface and through the debris layer [*Carenzo et al*., 2016] (Figure 2b). Further lags may relate to meltwater transit to the monitoring site. Transition in lag time between T_a and Q mid-season is ascribed to changes in weather systems and lapse rates reported for the region during the monsoon [e.g. *Shea et al*., 2015b, *Steiner and Pelliciotti* 2016], the reduction in both T_a and SW_{in}, and subtle changes in the hydrological function of the drainage system. The lack of association between Q and precipitation has been observed elsewhere on debris-covered glaciers [e.g. *Thayyen et al*., 2005]. However, the elongated diurnal hydrograph recession diverges notably from other glacial observations and more specifically recession data reported here evidence neither ‘fast’ supraglacial and ‘moderate’ en- and sub-glacial drainage flowpaths, superimposed on a ‘slow’ persistent baseflow on a diurnal basis, nor a seasonal decline in recession storage constants [cf. *Gurnell*, 1993]. Furthermore, the gauging station elevation (4930 m a.s.l.), ensures the Q record solely relates to the supraglacial (debris-covered) and shallow englacial environment. Observations during 2014 confirmed that some supraglacial meltwaters entered a shallow englacial network, potentially allowing flow between supraglacial ponds, evidenced by spatial variability in pond turbidity which suggested hydrological connectivity

(Figure 1e) [see *Takeuchi et al*., 2012]. While geomorphic signatures suggested that meltwater that had once drained or followed seepage pathways through other moraine breach locations, contemporary field observations indicate these are relict inactive features (IAOs: Fig. 1c). Consequently, we discuss our data in the context of a conceptual model of the dominantly supraglacial drainage system illustrated in Figure 3, comprising a debris layer punctuated by a cascade of lakes or ponds.

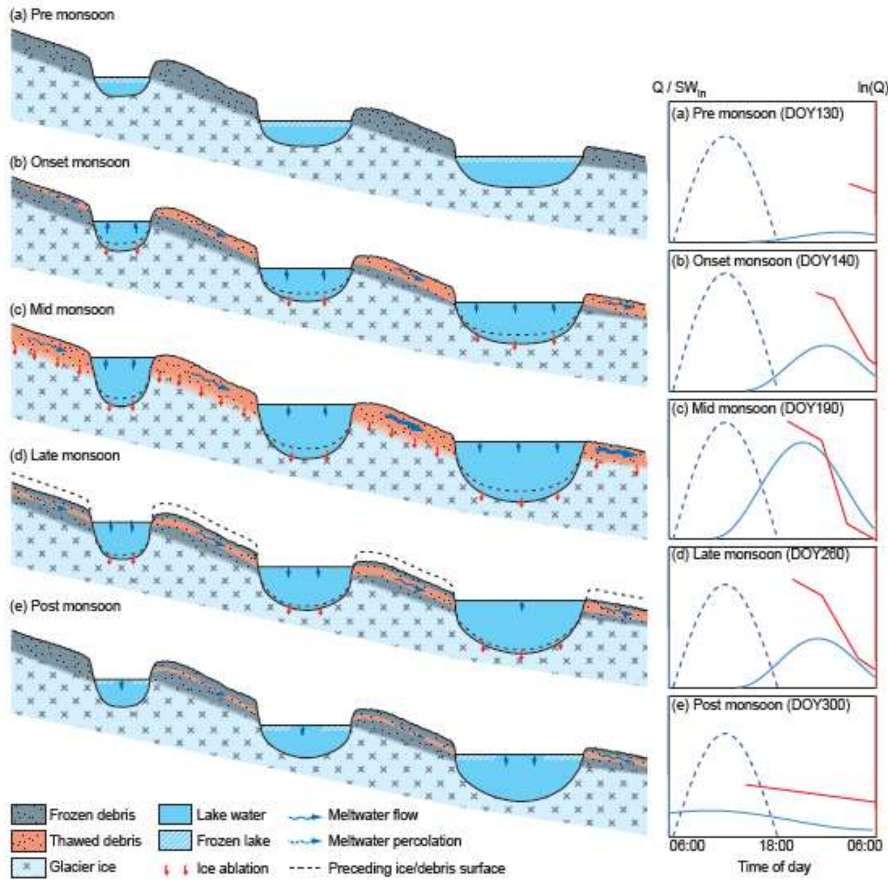


Figure 3: Conceptual model of the seasonal hydrological development of the surface of a Himalayan debris-covered glacier over an annual cycle. Indicative daily hydrometeorological plots for each stage are shown with SW_{in} (dashed), Q (blue), and a natural logarithmic transformed Q used to identify the recession components (red). Pre-monsoon (a) the surface is frozen following the winter period, but as the monsoon season approaches (b), the debris-cover begins to thaw, and water derived from melting intra-clast ice and ponds commences flow and thermal ablation at the base of ponds. Mid monsoon (c) the debris is fully thawed, ponds become connected and glacier ice melt occurs and ponds deepen through thermal ablation, which, coupled with monsoon rainfall, leads to more efficient drainage over the glacier ice surface. Towards the end of the monsoon season (d) the air temperatures drop and initiate freezing at the debris surface, while reductions in water flow facilitate upward freezing at the base of the debris layer; however, the thawed portion of the debris layer still transfers meltwater from ponds towards the glacier margin, albeit delayed. Post monsoon (e), which aligns with the latter portion

of our records, continued freeze-up of the lake and debris layer occurs restricting any transmission of meltwater as winter approaches and the glacier-wide hydrological system drains.

The cascade of developing ponds represents a series of reservoirs capable of temporarily storing meltwater and delaying its transit downstream. Combining the pre-monsoon pond areas (~ 2.5×10^5 m^2; Figure 1) with observation of the outflow lake level varying by ~0.7 m over a diurnal melt cycle, we estimate the supraglacial pond cascade on Khumbu Glacier to account for a minimum daily storage capacity of ~1.75×10^5 m^3 (equivalent to 23% of the observed mean daily discharge). Supported by evidence of progressive pond deepening during the monsoon season [e.g. *Watson et al*., 2017a] we conclude that the diurnal storage capacity of the pond system alone, not including the porous debris layer, can readily accommodate the observed daily mean P (~1.23×10^5 m^3 over the whole glacier area). The timing and magnitude of on-glacier storage may also be controlled by freeze-thaw processes, analogous to a periglacial environment given the local permafrost limit. During the winter, both the supraglacial debris layer and ponds are largely frozen, likely becoming impermeable and unable to convey any surface meltwater. As the monsoon season develops, the system progressively thaws [e.g. *Sakai et al*., 2000; *Benn et al.*, 2001; *Namara et al*., 2017; *Miles et al*., 2016; *Watson et al*., 2017a]. The ponds may become hydrologically linked by three key flowpaths: those within the debris-covered mantle; shallow debris-filled crevasses [e.g. *Benn et al*., 2012; *Gulley and Benn*, 2007] or channels formed from collapsed near-surface englacial conduits [*Miles et al*., 2017b]; or debris- or water-choked near-surface passages [*Watson et al*., 2017a]. Published figures for heterogeneous debris indicate permeability of between 10^{-2} to 10^{-6} m s^{-1} [*Parriaux and Nicoud*, 1990; *Muir et al*., 2011; *Woo and Steer*, 1983; *Gulley and Benn*, 2007] although mobilization of fines may further reduce hydraulic efficiency [*Woo and Xia*, 1995]. When thawed, therefore, we anticipate the debris layer and associated supraglacial and shallow or collapsed englacial features may act as a depth-limited, transient storage reservoir, regulating bulk meltwater discharge over the glacier surface and between ponds and hence moderating the overall diurnal flow variance. The debris layer is underlain by glacier ice with discrete, spatially limited, shallow englacial flowpaths analogous to continuous permafrost with isolated, closed talik. The result, in the monsoon-influenced climate, is a thermal regime dominated by the seasonal freezing and thawing of the debris layer, as is evident in our T_d time-series, and for which the correlations between T_a and T_d (Figure 2e) likely reflect change in debris heat capacity with water content. Khumbu Glacier's supraglacial debris layer may therefore be considered equivalent to a seasonally cryotic active layer [*Bonnaventure and Lamoureux*, 2013].

As the monsoon season progresses, evolution of the debris mantle hydrological system may result in increased inter-pond connectivity. Progressive thaw at depth in the debris layer and glacier ice melt, despite enlarging the supraglacial storage capacity, also aids the development of increasingly efficient supra-permafrost drainage: inter-clast ice is replaced with water flow pathways and increased hydraulic permeability [*Woo and Steer*, 1983; *Woo and Xia*, 1995], providing more efficient connections through the debris and facilitating debris-ice interface and englacial flowpath development [*Gulley and Benn*, 2007; *Gulley et al*., 2009; *Miles et al*., 2017b; *Watson et al*., 2017a]. Strengthening connectivity increases the rapidity of runoff through the cascading pond system. Sporadic activation, modification or abandonment of flowpaths and diurnal or seasonal variation in supraglacial pond storage capacity likely contributes to the observed variation of discharge recession (Fig. 3i). Such delay, peak flow suppression and attenuated recession, as seen in our data, are indicative of level-pool routing controlling meltwater transfer through a series of reservoirs [*Montaldo et al*., 2004] and, as such, the ponds may be conceptualized as thermokarst [*Kirkbride*, 1993].

Evidence for this role of supraglacial ponds and debris as regulators of meltwater discharge is exemplified by the diurnal hydrograph recession. When pond levels are at their peak or minima at seasonal and diurnal time-scales, K_P and K_B are determined by the hydraulic conductivity of the (thawed) debris that separates the individual pond basins. K_P was not clearly associated with either T_a or SW_{in} nor with daily maximum discharge; the recession segment was not associated with the magnitude of meltwater production. Once daily meltwater provision declines or ceases, changes in hydraulic head drive drainage through the pond cascade and the major recession (K_R) is governed by outflow channel geometry rather than rates of inflow controlled by debris permeability. K_R remains broadly consistent over the hydrologically active period (DOY134-270). Subsequently, particularly as T_a and T_d both fall and water drains from the pond cascade, water within the debris layer and debris-rich hydraulic connections between ponds refreezes, and the hydraulic efficiency of the system declines. This change is highlighted by $K_R > K_B$, the post-monsoon increase in K_R and a strongly negative, non-linear relationship between K_R and peak Q.

The observations following DOY 230 of declining Q despite positive T_a and T_d and precipitation contributions are counterintuitive. However, given our hydrological analysis and conceptual model it seems reasonable to suggest that this effect could have arisen from the fully thawed debris layer readily storing excess water produced in this period and mobilization of fines impinging on hydrological efficacy, with a consequent net reduction in throughflow evidenced by gradual increases in all K-values. The drainage of meltwater continued for ~45 days after night time T_a dropped to freezing, with around 7% of the observed runoff volume being delivered in this late- and post-monsoon period. This protracted drainage corresponds well to the delay in runoff thought to relate to hysteresis caused by a deep groundwater system in the Nepal Himalaya [*Andermann et al*., 2012]. Our data suggest that widespread supraglacial debris layers themselves may contribute to the observations of reservoir behavior in glacierized catchments at a seasonal timescale, and extend the duration of glacier meltwater delivery to downstream environments.

5 Conclusions

We have demonstrated that the evolving system of supraglacial ponds and accompanying debris has the capacity to act as a fundamental modulator of proglacial discharge regimes at Khumbu Glacier. Although there is uncertainty in the causal associations between glacier surface gradient, debris cover and pond occurrence [*Salerno et al*., 2017], supraglacial ponds are reported to be increasingly prevalent on debris-covered glaciers and represent an active and dynamic hydrological system [*Miles et al*., 2017a,b; *Narama et al*., 2017; *Watson et al*., 2016, 2017a]. Recently, there has been growing recognition that small changes in hydrological function in mountain regions can have substantial impacts on freshwater availability [e.g. *Pritchard*, 2017] and biodiversity [*Jacobsen et al*., 2012] in terrestrial water bodies and ecosystems in the Himalaya [*Xu et al*., 2009; *Salerno et al*., 2016]. To understand the hydrological response of debris-covered glaciers and to forecast changes in water resources and ecosystem services in the region, it is crucial to explicitly incorporate processes relating to the thermodynamics and hydrology of widespread debris mantles that can now be considered as cryotic, thermokarstic active layers – systems that are more commonly described solely in periglacial settings

[*Bonnaventure and Lamoureux*, 2013]. Further geophysical and hydrochemical exploration of debris cover [e.g. *Muir et al*., 2011; *McCarthy et al*., 2017] is needed to better define the nature of the supraglacial debris-covered drainage system and the modes and thermodynamics of hydraulic connectivity between ponds. With ~75 to 90% glacier area in the Himalaya above 4500–5000 m a.s.l., the elevation range commonly associated with the regional permafrost limit [*Schmidt et al*., 2015], processes we describe here should be widely applicable throughout the region and highlight the important role that debris-layer supraglacial hydrology may have on mediating glacier runoff characteristics in High Mountain Asia. Long-term increases in areal extent of debris cover and ponds will not only contribute to more rapid glacier mass loss but, we propose, also alter patterns of meltwater supply and quality to downstream catchments through their roles as temporary reservoirs and flow regulators. A more complete understanding of this buffering process is crucial to improving projections of the region's future water resources in a changing climate.

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