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The dynamics of supraglacial ponds in the Everest region, central Himalaya

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ABSTRACT

The dynamics of supraglacial pond development in the Everest region are not well constrained at a glacier scale, despite their known importance for meltwater storage, promoting ablation, and transmitting thermal energy englacially during drainage events. Here, we use fine-resolution (~0.5–2 m) satellite imagery to reveal the spatiotemporal dynamics of 9340 supraglacial ponds across nine glaciers in the Everest region, ~2000–2015. Six of our nine study glaciers displayed a net increase in ponded area over their observation periods. However, large inter- and intra-annual changes in ponded area were observed of up to 17% (Khumbu Glacier), and 52% (Ama Dablam) respectively. Additionally, two of the fastest expanding lakes (Spillway and Rongbuk) partially drained over our study period. The Khumbu Glacier is developing a chain of connected ponds in the lower ablation area, which is indicative of a trajectory towards large lake development. We show that use of medium-resolution imagery (e.g. 30 m Landsat) is likely to lead to large classification omissions of supraglacial ponds, on the order of 15–88% of ponded area, and 77–99% of the total number of ponds. Fine-resolution imagery is therefore required if the full spectrum of ponds that exist on the surface of debris-covered glaciers are to be analysed.

1. Introduction

The increased storage of meltwater in supraglacial, proglacial and ice-marginal settings is symptomatic of deglaciation and is a globally observed trend (Carrivick and Tweed, 2013). Glacial lake development across the central Himalaya (India, Nepal, Bhutan, Tibet (China)) (e.g. Komori, 2008; Gardelle et al., 2011; Nie et al., 2013; Veettil et al., 2015; Wang et al., 2015; Zhang et al., 2015) corresponds with warming temperatures and a trend of negative glacier mass balance (Kääb et al., 2012). The negative mass balance is well known to be modulated by the variable thickness of debris cover that promotes glacier surface lowering in conjunction with a relatively stable terminus position (Bolch et al., 2011). These mass balance trends and glacier characteristics are well documented in the Everest region (e.g. Bolch et al., 2008a, 2011; Benn et al., 2012; Ye et al., 2015), where surface lowering and increasing glacier stagnation has been highlighted to promote increased supraglacial pond formation and their potential coalescence into larger lakes where a low glacier surface gradient exists (Watanabe et al., 1994; Richardson and Reynolds, 2000; Quincey et al., 2007; Rohl, 2008; Thompson et al., 2012).

Glacier-scale observations of the links between areas of high downwasting and the location of ice cliffs and ponds, further reveal their importance for debris-covered glacier ablation (e.g. Immerzeel et al., 2014; Pellicciotti et al., 2015). Local-scale measurements and modelling of ice cliff retreat (e.g. Reid and Brock, 2014; Steiner et al., 2015) and pond energy balance (e.g. Sakai et al., 2000; Miles et al., 2016) have greatly improved process-based understanding in recent years. These ponds also play an important part in the glacier ablation budget, through the transmission of thermal energy to subaqueous ice and to adjacent ice cliffs (Sakai et al., 2000; Benn et al., 2001; Rohl, 2006; Miles et al., 2016). It may be hypothesised that ponds dynamics will be associated with patterns of glacier surface lowering and ice cliff calving. However, this hypothesis remains to be tested because quantitative measurements have hitherto been spatially limited to individual pond basins (e.g. Benn et al., 2001).

Studies focusing specifically on surface water storage in the Everest region have been regionally aggregated (e.g. Gardelle et al., 2011), glacier or lake specific (e.g. Bolch et al., 2008b; Thompson et al., 2012), or covering one point in time (e.g. Salerno et al., 2012) (Table 1). Whilst these approaches are merited, they are often limited by data availability, which has historically tended towards coarser-resolution imagery, and data suitability, which cannot be determined without ground-truth or fine-resolution imagery. In the Everest region and across the Himalaya previous studies have generally utilised 30 m resolution multi-spectral Landsat imagery, owing to the large temporal archive and simple band ratio application to delineate water bodies (e.g. Gardelle et al., 2011; Nie et al., 2013; Bhardwaj et al., 2015; Liu et al., 2015; Wang et al., 2015). ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) imagery (15 m resolution) is also popular for glacier-scale applications (e.g. Wessels et al., 2002; Bolch et al., 2008b; Thompson et al., 2012), although the archive is shorter (2000–present

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Table 1
Remote sensing studies of supraglacial water storage in the Everest region.

Reference	Date range	Coverage overlap with this study	Imagery (resolution)	Notes
Iwata et al. (2000)	1978–1995	Khumbu Glacier	SPOT (not specified)	A sketch map made with SPOT imagery was compared to that of a field survey in 1978
Wessels et al. (2002)	2000	Ngozumpa, Khumbu and Rongbuk glaciers	ASTER (15 m)	Band ratios were used to delineate water for a single time period. Turbid lakes were found in hydrologically connected regions
Bolch et al. (2008b)	1962–2005	Khumbu, Lhotse and Imja glaciers	Corona, Landsat, topographic maps, Iknos, ASTER (2–79 m)	Normalised Difference Water Index (NDWI) and/or manual delineation was used to classify water bodies.
Gardelle et al. (2011)	1990–2009	All glaciers	Landsat (30 m)	A decision tree was used to classify lakes incorporating the NDWI. A minimum lake size of 3600 m^2 was used. Area change was not reported for individual glaciers, other than a brief comparison with Bolch et al. (2008b). An association between negative mass balance and lake expansion is presented
Salerno et al. (2012)	2008	All except Rongbuk Glacier	AVNIR-2 (10 m)	Water bodies were manually digitised for a single time period
Thompson et al. (2012)	1984–2010	Ngozumpa Glacier	Aerial photographs (<1 m), ASTER (15 m)	A multi-temporal analysis of the expansion of Spillway Lake was conducted using satellite imagery and field surveys
Nie et al. (2013)	1990–2010	All glaciers	Landsat (30 m)	OBIA was combined with NDWI-based water detection. Ponded area change was not reported for individual glaciers.
Zhang et al. (2015)	1990–2010	All glaciers	Landsat (30 m)	Water bodies were manually digitised with a minimum lake size threshold of 2700 m^2. Ponded area change was not reported for individual glaciers.

Note: studies reporting the expansion of Imja Lake are not included.

day). Both sensors are limited by their spatial resolution, meaning associated studies have not been able to focus on detailed changes in ponds through time. This paper aims to present the first fine-resolution spatio-temporal analysis of supraglacial pond dynamics to address this shortcoming. We analyse Google Earth, Quickbird, GeoEye and WorldView imagery (0.7–2 m) covering nine glaciers in the Everest region of the central Himalaya. Our objectives are to: (1) characterise the spatial evolution of supraglacial ponds on an individual glacier scale; (2) quantify short-term seasonal and inter-annual change in supraglacial pond area in the region; and (3) evaluate the implications of using medium-resolution satellite imagery (e.g. 15–30 m) to delineate the full spectrum of pond sizes that exist on Himalayan debris-covered glaciers.

2. Study region

Annual precipitation in the Everest region is dominated by the Indian summer monsoon and the majority of rainfall (~80%) occurs between June–September (Bookhagen and Burbank, 2006; Wagnon et al., 2013). Both the northerly draining Rongbuk catchment and the southerly draining Dudh Koshi catchment display a trend of warming temperatures (Yang et al., 2006; Shrestha and Aryal, 2011), which in conjunction with a potentially delayed (Mölg et al., 2012) and/or weakening monsoon will reduce glacier accumulation (Salerno et al., 2015). Decreasing monsoonal precipitation is likely implicated in reduced glacier driving stresses, causing terminus stagnation and the subsequent development of supraglacial ponds and lakes in the region (Quincey et al., 2009; Salerno et al., 2015). The decadal response of large debris-covered glaciers to climate change suggests negative mass balance conditions will prevail in coming decades, irrespective of any slowdown to contemporary warming (Rowan et al., 2015).

The Everest region is characterised by glaciers that are heavily debris-covered in their lower reach (Fig. 1). The debris is sourced from rock fall avalanches and from moraine ridge collapses, and typically increases in thickness towards glacier termini (Nakawo et al., 1986). The glaciers are low gradient in the debris-covered area (Quincey et al., 2007), stagnating (Quincey et al., 2009; Dehecq et al., 2015), and are widely losing mass (Bolch et al., 2008a, 2011; Ye et al., 2015). Supraglacial ponds are prevalent features on the low gradient and hummocky topography of debris-covered glacier ablation zones. They vary in size, shape and turbidity (Fig. 2) as well as situation; some are surrounded by large, calving ice-cliffs whereas others sit in debris-lined hollows. The distinction between what may be described as a pond vs a lake is not well-defined (either theoretically or physically) so herein we refer to all surface water as ponds, unless specifically named otherwise (e.g. Spillway Lake on the Ngozumpa Glacier). Regardless of their size, the upper surface freezes over during the winter period (December–February), although a partially frozen surface may be present up to several months earlier.

Nine debris-covered glaciers in the Everest region spanning Nepal (8) and Tibet (1) were selected for supraglacial pond analysis (Fig. 1). These nine glaciers drain the Dudh Koshi and Rongbuk catchments respectively. The Rongbuk, Ngozumpa, and Khumbu glaciers are the longest in the study area with debris-covered lengths of ~15 km, ~11 km, and ~11 km, respectively; the shortest is Imja Glacier at ~2 km. The glaciers predominantly flow in a southerly direction with the exceptions of Rongbuk and Ama Dablam Glaciers (northerly flowing), and Imja Glacier (westerly flowing).

3. Data sources

This study used 16 time periods of fine-resolution imagery (Table 2), comprising nine from Google Earth (<2 m spatial resolution), and seven from WorldView 1 & 2, GeoEye, and QuickBird 2 sensors (0.5–0.6 m spatial resolution). This imagery incorporated post-monsoon/winter periods (termed winter herein) (late September–February), and pre-monsoon/monsoonal periods (termed summer herein) (March–mid September). True-colour orthorectified Google Earth images were accessed using Google Earth Pro. WorldView, GeoEye and Quickbird scenes were orthorectified in ERDAS Imagine using rational polynomial coefficients and the 30 m Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM). Glacier outlines were obtained from the South Asia — East Randolph Glacier Inventory 5.0 (Pfeffer et al., 2014). These outlines were modified manually to reflect the debris-covered area of each study glacier, and only supraglacial ponds falling within this masked area were included in the study.

4. Methods

4.1. Supraglacial pond classification

A total of 9340 ponds were classified in this study either semi-automatically using an object-based classification (46%), or manually digitised in Google Earth (54%).