HYDROLOGICAL PROCESSES
Hydrol. Process. **29**, 859–874 (2015)
Published online 11 April 2014 in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/hyp.10199

Rapid expansion of glacial lakes caused by climate and glacier retreat in the Central Himalayas

Weicai Wang,[1]* Yang Xiang,[1,3] Yang Gao,[1] Anxin Lu[2] and Tandong Yao[1]

[1] *Key Laboratory of Tibetan Environment Changes and Land Surface Processes, Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing 100101, China*
[2] *Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences, Beijing, China*
[3] *University of Chinese Academy of Sciences, Beijing, China*

Abstract:

Glacial lake outburst floods are among the most serious natural hazards in the Himalayas. Such floods are of high scientific and political importance because they exert trans-boundary impacts on bordering countries. The preparation of an updated inventory of glacial lakes and the analysis of their evolution are an important first step in assessment of hazards from glacial lake outbursts. Here, we report the spatiotemporal developments of the glacial lakes in the Poiqu River basin, a trans-boundary basin in the Central Himalayas, from 1976 to 2010 based on multi-temporal Landsat images. Studied glacial lakes are classified as glacier-fed lakes and non-glacier-fed lakes according to their hydrologic connection to glacial watersheds. A total of 119 glacial lakes larger than 0.01 km^2 with an overall surface area of 20.22 km^2 (±10.8%) were mapped in 2010, with glacier-fed lakes being predominant in both number (69, 58.0%) and area (16.22 km^2, 80.2%). We found that lakes connected to glacial watersheds (glacier-fed lakes) significantly expanded (122.1%) from 1976 to 2010, whereas lakes not connected to glacial watersheds (non-glacier-fed lakes) remained stable (+2.8%) during the same period. This contrast can be attributed to the impact of glaciers. Retreating glaciers not only supply meltwater to lakes but also leave space for them to expand. Compared with other regions of the Hindu Kush Himalayas (HKH), the lake area per glacier area in the Poiqu River basin was the highest. This observation might be attributed to the different climate regimes and glacier status along the HKH. The results presented in this study confirm the significant role of glacier retreat on the evolution of glacial lakes.

KEY WORDS glacial lake; glacial lake outburst flood; Poiqu River basin; Landsat; natural hazards

Received 28 January 2014; Accepted 18 March 2014

INTRODUCTION

It is widely accepted that the majority of glaciers on the Tibetan Plateau are now retreating and thinning (Bolch *et al.*, 2012; Yao *et al.*, 2012), although spatially systematic differences in glacier status are apparent (Yao *et al.*, 2012) and the exact mass loss remains controversial (Jacob *et al.*, 2012; Kääb *et al.*, 2012; Gardner *et al.*, 2013). Glacial retreat on the Tibetan Plateau not only affects water resources (Yao *et al.*, 2004), runoff regimes (Immerzeel *et al.*, 2010; Sorg *et al.*, 2012) and hydrological processes (Yao *et al.*, 2007) in the region but also causes the formation and development of glacial lakes (Richardson and Reynolds, 2000; Quincey *et al.*, 2007; Nayar, 2009; Sakai and Fujita, 2010) on/beneath/in front of mother glaciers (Raj *et al.*, 2013). Such glacial lakes can be storehouses of fresh water (Komori, 2008; Mergili *et al.*, 2013), but they are also hazardous to humans and infrastructure as they can suddenly drain and cause devastating glacial lake outburst floods (GLOFs) downstream (Richardson and Reynolds, 2000; Kääb *et al.*, 2005; Benn *et al.*, 2012).

A number of GLOFs have occurred on the Tibetan Plateau in the last several decades (Lü, 1999), and the majority have been concentrated in the Himalayas and the region south-east of the Tibetan Plateau (Ding and Liu, 1992; Wang *et al.*, 2011a, b; 2012b). Previous GLOF events have demonstrated that glacial lakes are a potential threat to people living downstream because of their suddenness and the large land area that is affected. Some GLOFs have also caused considerable damage across international borders. An outburst of a glacial lake in one country in the trans-boundary basin may cause damages to neighbouring countries, e.g. the Cirenmaco outburst flood in 1981 (Xu, 1988).

The Poiqu River basin is a highly GLOF-prone trans-boundary basin in the Central Himalayas (Shrestha *et al.*, 2010). Rapid glacier retreat and intense rainfall in the monsoon season (Liu and Sharmal, 1988; Chen *et al.*, 2007a)

*Correspondence to: Weicai Wang, Key Laboratory of Tibetan Environment Changes and Land Surface Processes, Institute of Tibetan Plateau Research, Chinese Academy of Sciences, No. 16 Lincui Road, Chaoyang District, Beijing 100101, China.
E-mail: weicaiwang@itpcas.ac.cn

make this area one of the most GLOF-affected regions of the Tibetan Plateau. The Poiqu River basin has experienced at least four GLOF events in the past 70 years (Taraco in 1935, Cirenmaco in 1964 and 1981 and Jialongco in 2002). The most severe was the 1981 Cirenmaco GLOF, whose maximum outburst discharge was estimated to be 16 000 m^3/s and occurred only 23 min after the initial outburst (Xu, 1988). The main bursting flood lasted for an hour and discharged approximately 19 000 000 m^3 of burst water, which is more than 16 times the annual mean discharge. Nearly 4 000 000 m^3 of debris was carried in the floodwaters. The 1981 Cirenmaco GLOF destroyed the China–Nepal Friendship Bridge and the Sun-Kosi Hydropower Station, swept away 200 people in Nepal and severely damaged approximately 27 km of road (Xu, 1988; Bajracharya *et al*., 2007; Shrestha *et al*., 2010). With global warming and glacial retreat, the frequency of GLOFs appears to have increased in recent years (Richardson and Reynolds, 2000), and GLOF hazards in the Poiqu River basin are envisaged to increase significantly in the near future. A GLOF hazard assessment has therefore become a relevant need in the basin (Shrestha *et al*., 2010).

An updated and standardized glacial lake inventory constitutes the first important step for GLOF hazard assessment (Huggel *et al*., 2004; Frey *et al*., 2010; Wang *et al*., 2012b, 2013a; Nie *et al*., 2013). Such a multi-temporal inventory will provide the basis for analysing the spatial distribution and temporal development of glacial lakes and allow the identification of potentially dangerous glacial lakes (Wang *et al*., 2011a, 2012c) and/or modelling of GLOFs (Wang *et al*., 2008, 2012a). The first glacial lake inventory in the Poiqu River basin was reported by Liu and Sharmal (1988). That work was an achievement of the first joint Sino-Nepalese GLOF study expedition to the upper reaches of the Pumqu and Poiqu River basins in Tibet, China, and took place during April–June 1987. Using a few investigated glacial lakes as validation, Liu and Sharmal (1988) catalogued glacial lakes using aerial photographs taken in 1974 at a scale of 1 : 60 000 and topographic maps from 1981 at a 1 : 100 000 scale (Liu and Sharmal, 1988). They found a total of 45 glacial lakes with an overall surface area of 12.31 km^2. A relatively new glacial lake inventory was thereafter prepared by Chen *et al*. (2007a) using the Landsat Multispectral Scanner (MSS) of 1986 and the Landsat Thematic Mapper of 2001. In 1986, the total glacial lake surface area was found to be 12.01 km^2 and expanded to 17.56 km^2 in 2001. Recently, Wang *et al*. (2012d) also performed a thorough inventory of glacial lakes for the entire Chinese Himalaya, including the Poiqu River basin, with ASTER remotely sensed data from the 2000s. They identified 63 glacial lakes with a total surface area of 14.77 km^2. Thus, the existing lake inventory for the Poiqu River basin is based on a variety of data sources from the 1970s, 1990s and 2000s, leaving a gap in knowledge over the most recent decade. With its geographic importance, the Poiqu River basin urgently needs an up-to-date glacial lake inventory.

To address this need, this study provides an updated and complete outline of the glacial lakes in the Poiqu River basin using multi-temporal Landsat images. By analysing multiple phases of glacial lake inventories, we also investigate the distribution and development of glacial lakes in the Poiqu River basin from 1976 to 2010, with a special focus on the last decade. Our results are then linked to climate change and glacier fluctuations, to demonstrate how climate and glacier activity affect the status of glacial lakes.

STUDY AREA

The Poiqu River is a trans-boundary river that originates on the southern slopes of the Central Himalayas and flows southward into Nepal, where the river is called Bhote-Sun-Kosi (Shrestha *et al*., 2010). The ten main tributaries of the Poiqu River are the Lazapu, Tongpu, Koryagpu, Qiongrepu, Rujiapu, Targyailing, Duomupu, Jipu, Congduipu and Zhangzangbo (Figure 1). The river's total length is approximately 81 km, and its annual mean discharge is 31.7 m^3/s (Chen *et al*., 2007a).

The Poiqu River basin (27°54′–28°30′N; 85°42′–86° 21′E) is leaf shaped and has a total area of 2018 km^2 (Liu and Sharmal, 1988). Its elevation ranges from 1178 to 8012 m (peak of Mt Xixabangma). An important highway linking Nepal and China winds along the Poiqu River. Glaciers and glacial lakes appear on both sides of the main valley. According to our new inventory, in 2010, the region contained 124 glaciers and 69 lakes with total areas of 203.4 and 19.55 km^2, respectively.

The Poiqu River basin is directly controlled by the Indian monsoon and is characterized by a humid subtropical mountain climate. With increasing elevation, temperature and precipitation decrease gradually from south to north. The annual mean temperature (6-year average from 2006 to 2011) is 12.8 °C at Zhangmu [2480 m above sea level (a.s.l.), Figure 1], with the maximum occurring in July (17 °C) and the minimum occurring in January (1.5 °C), according to meteorological data recorded by a newly installed Automatic Weather Station (Prof. Lide Tian, personal communication). Annual mean temperature decreases to 3.7 °C (6-year average from 2006 to 2011) at the Nyalam Meteorological Station (3810 m a.s.l., Figure 1), with maximum and minimum temperatures also occurring in July and January, respectively. Annual precipitation is 2820 mm at Zhangmu and decreases to 650 mm at Nyalam (Chen *et al*., 2007a), whereas ~60% of the precipitation occurs in the summer (June to September).

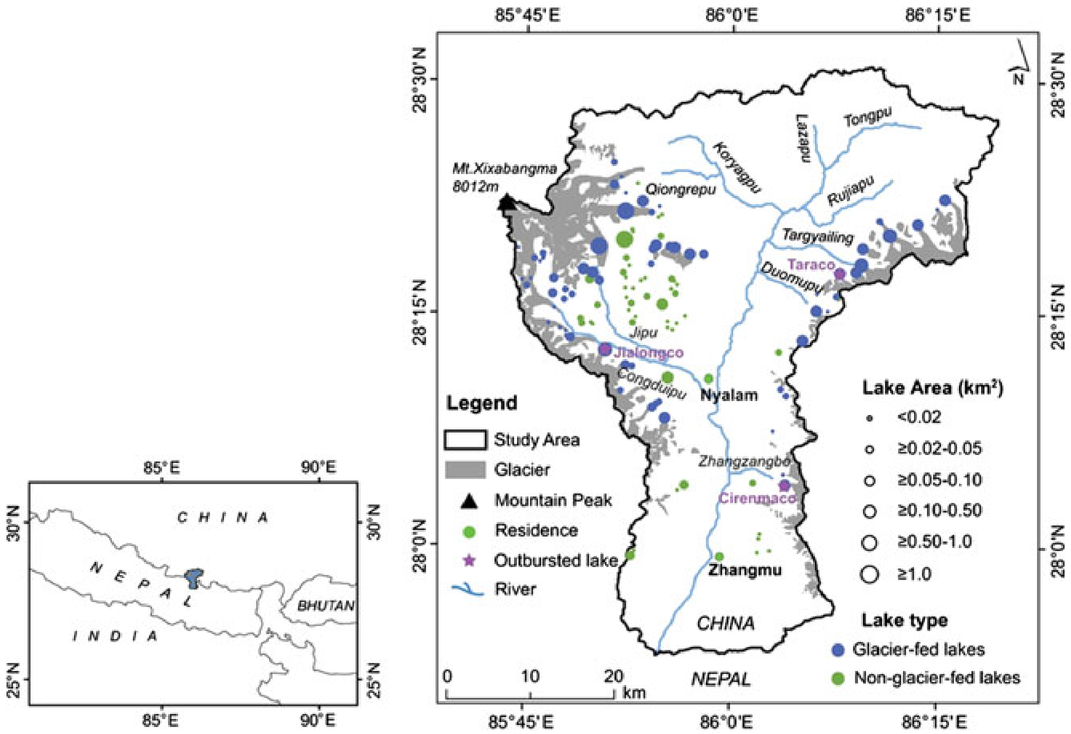

Figure 1. Poiqu River basin and the distribution of glacial lakes in the basin in 2010. Delineation of the boundary of Poiqu River basin is based on Shuttle Radar Topography Mission (SRTM) and topographic maps. Glacier outlines are from Landsat images acquired in September, 2000

DATA AND METHODS

Satellite data

Multi-temporal Landsat images from 1976 to 2010 were used in this study to inventory the glacial lakes in the Poiqu River basin and to study variations in the glacial lakes. The Landsat images (L1T) were downloaded from the International Scientific and Technical Data Mirror Site, Computer Network Information Center, Chinese Academy of Sciences (http://www.gscloud.cn). The images were provided ortho-rectified and projected in World Geodetic System-Universal Transverse Mercator. Only the Landsat images acquired from late August to early December were chosen to avoid the high cloud obscuration during the monsoon season and ensure minimal snow coverage. For each phase of the glacial lake inventory, several images acquired on consecutive dates were used to ensure the reliable delineation of the glacial lakes' boundaries. Detailed information on the Landsat images used in this study is provided in Table I.

A 25-m digital elevation model (DEM) produced by the National Geomatics Center of China was also used in this study to derive the elevation of glacial lakes and to delineate watersheds for each of the lakes. The DEM was created from 1 : 50 000-scale topographic maps with a 20-m contour line interval that was constructed from aerial photography in the 1970s (Wang *et al*., 2012a).

Glacial lake inventory

Some researchers have reported automated or semi-automated methods for digitizing glacial lakes (Huggel *et al*., 2002; Gardelle *et al*., 2011; Li and Sheng, 2012) and glaciers (Paul *et al*., 2002; Bhambri and Bolch, 2009); however, those methods are more suitable to larger areas and still require manual correction. Hence, glacial lakes and their mother glaciers were manually identified and digitized on the basis of false-colour composite Landsat images.

For the new inventory of glacial lakes in 2010, lakes larger than 0.01 km^2 (Worni *et al*., 2013) were digitized and catalogued according to the following attributes:

1. Number: For consistency, we assign the same number used for previous glacial lake inventories, e.g. Liu and Sharmal (1988) and Chen *et al*. (2007a).
2. Name: Some glacial lakes have local Tibetan names.
3. Longitude and latitude: The World Geodetic System 1984 coordinates for the centre of the glacier lake.
4. Elevation: The elevation above sea level at the water surface.
5. Area: The area of the glacial lake was automatically calculated in ArcGIS with a vectorized glacial lake layer.
6. Orientation: The drainage direction of the glacial lake is specified as one of eight positions (N, NE, E, SE, S, SW, W and NW; represented by numbers 1–8, respectively).

Table I. Landsat imagery used for delineating the glacial lake inventory

Phase	Date	Image type	Scene identification no.	Path/row	Resolution (m)	Cloud cover (%)
1976	2-Nov-75	MSS	LM21510411975306AAA05	151/41	90	10
	20-Dec-76	MSS	LM21510401976355AAA04	151/40	90	0
1991	30-Nov-91	TM	LT41410401991334XXX02	141/40	30	10
	30-Nov-91	TM	LT41410411991334XXX02	141/41	30	20
2000	5-Oct-00	ETM+	LE71410402000279SGS00	141/40	15	12
	30-Oct-00	ETM+	LE71400412000304SGS00	140/41	15	0
	22-Nov-00	ETM+	LE71410402000327EDC00	141/40	15	1
	22-Nov-00	ETM+	LE71410412000327EDC00	141/41	15	8
2010	15-Oct-09	TM	LT51400412009288KHC00	140/41	30	10
	22-Oct-09	TM	LT51410402009295KHC00	141/40	30	27
	9-Dec-09	TM	LT51410412009311KHC00	141/41	30	0
	25-Aug-11	TM	LT51410402011237KHC00	141/40	30	26

MSS, multispectral scanner; TM, thematic mapper; ETM+, enhanced thematic mapper plus.

7. Type: In the Poiqu River basin, we classified glacial lakes as glacier-fed lakes and non-glacier-fed lakes according to their hydrologic connection with their mother glaciers. We used DEM to delineate watersheds for each lake and identify whether it was connected to glaciers upstream. Glacier-fed lakes are those connected to glacial watersheds and thus with direct glacial meltwater supply, whereas non-glacier-fed lakes are those not connected to glacial watersheds. Glacier-fed lakes include supraglacial lakes and proglacial lakes, most of which are dammed by loose moraine ridges. Non-glacier-fed lakes include those periglacial lakes and are mostly those glacial erosion lakes and trough valley lakes that formed in overdeepenings left by vanishing Quaternary glaciers.
8. Length: Measured along the long axis of the lake and estimated to 0.1 km.
9. Width: Typically calculated by dividing the area of the lake by its length and estimated to 0.1 km.
10. Distance to glacier: The closest point to the glacier and estimated to 0.1 km. Only applied to glacier-fed lakes.

Glacial lake development

For the development of glacial lakes from 1976 to 2010 based on multi-temporal Landsat images, only glacial lakes larger than 0.02 km^2 were analysed, considering the relatively low resolution of the Landsat MSS. Chen *et al.* (2007a) also set 0.02 km^2 as the threshold value for studying glacial lakes in the Poiqu River basin. This threshold enables the results to be accurately compared.

Identification of potentially dangerous glacial lakes

The identification of potentially dangerous glacial lakes by remote sensing is challenging and has inspired numerous approaches on the part of researchers, e.g. Huggel *et al.* (2004), Chen *et al.* (2007b),McKillop and Clague (2007a, b), Bolch *et al.* (2011), Mergili and Schneider (2011), Wang *et al.* (2011a, 2012c), Fujita *et al.* (2013) and Gruber and Mergili (2013). Emmer and Vilímek (2013) conducted a comprehensive review of a number of methods and found that each method has both advantages and disadvantages.

Using the method previously developed in the southeastern Tibetan Plateau (Wang *et al.*, 2011a), we reassessed the stability of glacial lakes in the Poiqu River basin. By analysing earlier glacial lake outburst cases in the Himalayas, one can conclude that the cause of the outbursts was mostly ice avalanches on the mother glacier tongue (Ding and Liu, 1992; Lü, 1999). Therefore, we applied five variables – mother glacier area, distance between the lake and the glacier terminus, slope between the lake and the glacier, mother glacier snout steepness and mean slope of the moraine dam – to assess the lakes' stabilities. A fuzzy consistent matrix method was then applied to determine the weighting (w) of these variables. The threshold values were determined for each variable using a statistical distribution method (median, 25th and 75th percentiles). These threshold values were used to classify each individual variable into four intervals, and each interval was given a danger value (V) from 0.25 to 1. The degree of danger (P) for a glacial lake was calculated as the sum of each individual danger value (V) multiplied by its respective weighting value (w).

$$P = \sum_{i=1}^{5} w_i \cdot V_i$$

This semi-quantitative method is valuable for GLOFs caused by ice avalanches because all the selected variables are related to ice avalanches affecting the glacial lakes. However, other factors can also cause GLOFs. For example, a recent study shows that glacial de-buttressing and permafrost degradation can decrease slope stability in high-altitude rock walls, resulting in rock walls sliding into lakes, causing outbursts (Haeberli, 2013). Our method, therefore, only applies to the scenario of lake outburst as a consequence of impact waves from ice avalanches.

Uncertainty analysis

The accuracy of the delineation of glacial lakes is primarily determined by (i) co-registration errors, u_c (in pixels); (ii) image resolution, u_r (in percentage); and (iii) the experience of the operator, u_o (in percentage) (Hall *et al.*, 2003; Wang *et al.*, 2012d). In this study, the error in image co-registration (u_c) does not play a key role because the comparison of the glacial lake areas is not made pixel by pixel but rather entity by entity (Salerno *et al.*, 2012). We estimate the uncertainty of the Landsat-based measurement of glacial lakes introduced by image resolution (u_r) on the basis of the methods provided by other researchers (e.g. Fujita *et al.*, 2008, 2009; Wang *et al.*, 2011b; Salerno *et al.*, 2012). These authors assumed the shoreline of the glacial lake passes through the centre of the pixel, giving an uncertainty of 0.5 pixels. Therefore, the uncertainty can be calculated as a function of the pixel resolution and perimeter and expressed in percentage relative to the lake area. As a consequence, the uncertainty for small glacial lakes is proportionally larger than that for large lakes (Salerno *et al.*, 2012). The error introduced by the operator (u_o) depends primarily on her or his experience. To estimate this, the glacial lakes in the 2010 Landsat images were delineated by two other colleagues, and the differences between the three operators were within 3%. We therefore estimate the uncertainty caused by the operator to be 3%. The overall uncertainty (u, in percentage) of the glacial lake measurements was estimated as follows.

$$u = \sqrt{u_r^2 + u_o^2}$$

RESULTS

Glacial lake inventory of 2010

A total of 119 glacial lakes with individual areas larger than 0.01 km^2 were identified on the basis of Landsat images from 2010, with an overall area of 20.22 km^2 (±10.8%). Table II provides a general summary of each glacial lake. According to their hydrologic connection to glacial watersheds, the glacial lakes in the Poiqu River basin are classified as glacier-fed lakes (including proglacial lakes and supraglacial lakes) and non-glacier-fed lakes (periglacial lakes). Glacier-fed lakes have a total number of 69 and an overall surface area of 16.22 km^2 (±9.8%), which account for 58.0% and 80.2% of the total glacial lakes, respectively, in number and area. Non-glacier-fed lakes were fewer in number and area and sparsely distributed in the study area. Previous studies have demonstrated that the most dangerous glacial lakes on the Tibetan Plateau are the supraglacial lakes and proglacial lakes that are dammed by loose moraine ridges (Liu and Sharmal, 1988; Ding and Liu, 1992).

Glacial lakes in the Poiqu River basin have developed on both sides of the Poiqu River and are more densely distributed on the western side (Figure 1). The glacier-fed lakes are more evenly distributed over the basin than the non-glacier-fed lakes, which are concentrated in the Jipu sub-basin on the south-east slope of Mt Xixabangma (cf. Figure 1).

The majority of the glacial lakes in the Poiqu River basin are tiny ($A < 0.02$ km^2) or small ($0.02 \leq A < 0.05$ km^2), with these two size classes comprising nearly 70% of the total (Figure 2a). Medium-sized ($0.05 \leq A < 0.1$ km^2), large-sized ($0.1 \leq A < 0.5$ km^2) and giant-sized (≥0.5 km^2) glacial lakes, although less in number, account for 91.7% of the total glacial lake area. Glacier-fed lakes display a larger average area than non-glacier-fed lakes (0.24 *vs* 0.08 km^2, Table III). The largest glacier-fed lake in the Poiqu River basin is Galongco (glacial lake no. 14), which is located on the south-eastern side of Mt Xixabangma and has an area of 4.83 km^2.

Glacial lakes are distributed within the altitudinal range of 4120–5860 m, and the majority of them, as can be seen in Figure 2b, are situated at an elevation of ≥5000 m, accounting for 75.6% and 88.9% of the total number and area. Glacier-fed lakes have an average elevation 100 m higher than non-glacier-fed lakes (5192 *vs* 5027 m, Table III). We also found that the higher elevation, the greater is the number of glacier-fed lakes than non-glacier-fed lakes (Figure 2b). This observation is expected, as modern glacier termini where glacier-fed lakes are located are higher in elevation than the ponds left by Quaternary glaciers that have disappeared where non-glacier-fed lakes are usually located.

Glacial lake evolution from 1976 to 2010

The Poiqu River basin has experienced significant growth in both the number and area of glacial lakes from 1976 to 2010. Table IV summarizes the details for the glacial lakes for four periods. The total area of glacial lakes increased by 83.1% in the last 34 years, with the expansion rate reaching 0.26 km^2 year^{-1}. We also discovered that glacier-fed lakes exhibit a contrasting pattern with non-glacier-fed ones: Whereas the former exhibited a continuous and accelerated expansion from 1976 to 2010, the latter exhibited a moderate and stable trend over the same period (Table IV).

We also tracked individual glacial lakes for the study period from 1976 to 2010 to address the evolution process of each lake (Figure 3). The lake status in each period can be grouped into four categories: emerging lakes (those not detected in a previous phase), growing lakes (lake area

Table II. Inventory of glacial lakes in 2010

No.	Name	Longitude (°)	Latitude (°)	Elevation (m)	Area (km^2)	Aspect	Type	Length (km)	Width (km)	Distance to mother glacier (km)
1		85.94	28.07	4529	0.053	7	N	0.3	0.2	
2	Daroco	85.92	28.18	4355	0.466	1	N	1.0	0.5	
3		85.88	28.19	4621	0.028	1	G	0.4	0.1	0.3
4	Nongjue	85.87	28.19	4620	0.073	8	G	0.4	0.2	0.3
5	Jialongcuo	85.85	28.21	4381	0.604	2	G	1.3	0.5	1.1
6		85.80	28.22	4751	0.052	3	G	0.4	0.1	0.3
7		85.78	28.27	5318	0.080	3	G	0.5	0.2	0.3
8		85.80	28.28	5384	0.026	4	G	0.2	0.1	0.2
9		85.82	28.24	5036	0.038	5	N	0.3	0.1	
10		85.82	28.24	5089	0.031	5	N	0.3	0.1	
11		85.83	28.29	5045	0.078	2	N	0.4	0.2	
12		85.83	28.29	5023	0.289	8	G	0.8	0.4	0.6
13*		85.82	28.30	5091	0.284	2	G	1.0	0.3	0.0
14*	Galongco	85.84	28.32	5078	4.828	1	G	4.1	1.2	0.2
15	Gungco	85.87	28.33	5167	2.207	1	N	2.1	1.1	
16		85.87	28.31	5285	0.037	2	N	0.3	0.1	
17		85.88	28.26	5216	0.028	3	N	0.3	0.1	
18		85.90	28.27	5252	0.044	8	N	0.4	0.1	
19	Colungco	85.92	28.26	5107	0.277	1	N	1.0	0.3	
20		85.93	28.27	5302	0.046	8	N	0.3	0.1	
21		85.93	28.29	5142	0.031	7	N	0.2	0.2	
22		85.97	28.31	5121	0.064	1	G	0.4	0.2	0.3
23	Xiahu	85.95	28.31	5229	0.314	3	G	0.7	0.5	0.5
24	Mulaco	85.93	28.32	5306	0.117	3	G	0.6	0.2	0.5
25		85.92	28.32	5333	0.087	1	G	0.5	0.2	0.4
26	Mabiya	85.91	28.32	5394	0.152	2	G	0.5	0.3	0.3
27*	Gangxico	85.87	28.36	5226	4.605	2	G	5.0	0.9	0.0
28	Yinraco	85.89	28.37	5242	0.308	1	G	0.6	0.5	0.5
29		86.26	28.37	5552	0.214	1	G	0.8	0.3	0.6
30*	Youmojanco	86.23	28.35	5359	0.492	8	G	1.5	0.3	0.0
31	Cawuqudenco	86.19	28.34	5423	0.571	1	G	1.4	0.4	1.3
32	Gangpuco	86.16	28.32	5550	0.228	1	G	0.7	0.3	0.4
33	Paquci	86.16	28.30	5309	0.621	1	G	2.1	0.3	1.9
34	Southhu	86.15	28.30	5346	0.171	1	G	0.7	0.2	0.6
35	Taraco	86.13	28.29	5245	0.257	2	G	1.1	0.2	0.9
36		86.13	28.27	5554	0.043	5	G	0.3	0.1	0.3
37		86.10	28.25	5192	0.166	5	G	0.8	0.2	0.5
38	Agazidico	86.06	28.21	4977	0.030	6	N	0.2	0.1	
39		86.06	28.17	5170	0.046	4	G	0.3	0.2	0.2
40		86.07	28.16	5166	0.021	5	G	0.2	0.1	0.1
41		86.05	28.12	4583	0.017	2	G	0.2	0.1	0.1
42*	Cirenmaco	86.07	28.07	4639	0.325	7	G	1.1	0.3	0.9
43		86.03	28.07	4502	0.035	7	N	0.3	0.1	
44		86.04	28.01	4271	0.010	2	N	0.1	0.1	
45		86.03	28.01	4435	0.016	2	N	0.2	0.1	
46		85.84	28.29	4976	0.062	8	G	0.3	0.2	0.1
47*		85.76	28.31	5505	0.026	5	G	0.2	0.1	0.1
48		85.78	28.29	5429	0.059	5	G	0.4	0.2	0.3
49		85.91	28.15	4488	0.033	4	G	0.3	0.1	0.2
50		85.91	28.16	4484	0.022	1	G	0.2	0.1	0.1
51		85.90	28.15	4497	0.078	5	G	0.3	0.3	0.1
52		85.86	28.41	5586	0.039	5	G	0.3	0.1	0.2
53		85.87	28.17	4688	0.042	5	G	0.4	0.1	0.3
54		85.90	28.32	5440	0.050	2	G	0.3	0.2	0.2
55		86.09	28.22	5178	0.103	4	G	0.4	0.2	0.3
56		85.92	28.14	4879	0.101	1	G	0.4	0.3	0.3
57		85.86	28.39	5416	0.050	2	G	0.3	0.2	0.3
58		85.88	27.99	4120	0.055	3	N	0.4	0.2	

(Continues)

Table II. (Continued)

No.	Name	Longitude (°)	Latitude (°)	Elevation (m)	Area (km^2)	Aspect	Type	Length (km)	Width (km)	Distance to mother glacier (km)
59		85.88	28.00	4288	0.010	7	N	0.1	0.1	
60		85.94	28.06	4642	0.015	3	N	0.2	0.1	
61	Emaco	86.03	27.99	4268	0.019	3	N	0.2	0.1	
62	Dareco	86.05	28.00	4287	0.020	4	N	0.2	0.1	
63		85.80	28.27	5271	0.044	6	G	0.4	0.1	0.2
64*		85.81	28.27	5393	0.023	8	G	0.2	0.1	0.1
65		85.77	28.31	5614	0.031	5	G	0.3	0.1	0.2
66		85.77	28.31	5596	0.019	5	G	0.2	0.1	0.1
67		86.10	28.27	5470	0.020	6	G	0.2	0.1	0.1
68		86.10	28.26	5213	0.012	7	G	0.2	0.1	0.1
69		86.13	28.27	5524	0.015	4	N	0.2	0.1	
70		86.18	28.35	5362	0.025	8	G	0.3	0.1	0.1
71		86.18	28.35	5369	0.014	7	G	0.1	0.1	0.1
72		85.89	28.39	5414	0.020	1	N	0.3	0.1	
73		85.91	28.36	5184	0.014	1	N	0.2	0.1	
74	Coqiongniba	85.91	28.35	5196	0.019	8	N	0.3	0.1	
75		85.91	28.33	5330	0.023	8	N	0.2	0.1	
76		85.88	28.34	5178	0.015	5	N	0.2	0.1	
77		85.88	28.34	5174	0.010	6	N	0.1	0.1	
78		85.84	28.26	4980	0.032	3	N	0.2	0.1	
79		85.83	28.24	5003	0.013	5	N	0.2	0.1	
80		85.88	28.24	5201	0.021	2	N	0.2	0.1	
81		85.88	28.25	5115	0.015	3	N	0.2	0.1	
82		85.87	28.27	5295	0.010	2	N	0.1	0.1	
83		85.87	28.28	5197	0.019	2	N	0.2	0.1	
84		85.88	28.28	5140	0.012	2	N	0.2	0.1	
85		85.89	28.29	5246	0.018	8	N	0.2	0.1	
86		85.87	28.29	5217	0.030	3	N	0.2	0.1	
87		85.88	28.30	5276	0.019	3	N	0.2	0.1	
88		85.90	28.30	5432	0.021	4	G	0.3	0.1	0.6
89		85.90	28.36	5182	0.028	3	G	0.3	0.1	0.2
90		85.91	28.37	5080	0.018	1	G	0.2	0.1	0.2
91		85.88	28.25	5324	0.014	5	N	0.2	0.1	
92		86.06	28.08	4612	0.011	7	G	0.2	0.1	0.1
93		85.78	28.26	5030	0.010	3	G	0.2	0.1	0.1
94		85.77	28.31	5595	0.010	2	G	0.2	0.1	0.1
95		86.12	28.25	5305	0.014	1	G	0.2	0.1	0.1
96		85.89	28.29	5227	0.014	7	N	0.2	0.1	
97		86.25	28.36	5682	0.012	7	G	0.2	0.1	0.1
98		85.87	28.29	5193	0.013	2	N	0.2	0.1	
99		85.93	28.29	5144	0.011	4	N	0.2	0.1	
100		85.93	28.28	5122	0.015	2	N	0.2	0.1	
101		85.93	28.28	5281	0.014	1	N	0.2	0.1	
102		85.92	28.24	5175	0.016	1	N	0.2	0.1	
103		85.93	28.24	5070	0.016	2	N	0.2	0.1	
104		85.92	28.24	5317	0.013	1	N	0.1	0.1	
105		85.93	28.23	5204	0.013	1	N	0.2	0.1	
106		85.86	28.40	5416	0.014	4	G	0.2	0.1	5.3
107		85.87	28.38	5536	0.017	5	G	0.1	0.1	0.1
108		85.83	28.24	4998	0.010	6	N	0.1	0.1	
109		85.77	28.31	5573	0.016	7	G	0.2	0.1	0.1
110		85.76	28.29	5224	0.011	5	G	0.1	0.1	0.1
111		85.74	28.29	5434	0.012	4	G	0.2	0.1	0.1
112		85.75	28.28	5312	0.024	2	G	0.2	0.1	0.1
113		85.78	28.24	5076	0.012	5	G	0.1	0.1	0.1
114		85.78	28.24	5082	0.010	3	G	0.1	0.1	0.1
115		85.79	28.23	4983	0.011	1	G	0.1	0.1	0.1
116		85.80	28.23	4933	0.014	2	G	0.1	0.1	0.1

(Continues)

Table II. (Continued)

No.	Name	Longitude (°)	Latitude (°)	Elevation (m)	Area (km^2)	Aspect	Type	Length (km)	Width (km)	Distance to mother glacier (km)
117		85.80	28.23	4853	0.010	2	G	0.2	0.1	0.1
118		85.94	28.25	5296	0.010	1	N	0.1	0.1	
119		85.74	28.32	5857	0.011	3	G	0.1	0.1	0.1

G, glacier-fed lake; N, non-glacier-fed lake; aspects 1–8 represent N, NE, E, SE, S, SW, W and NW, respectively.

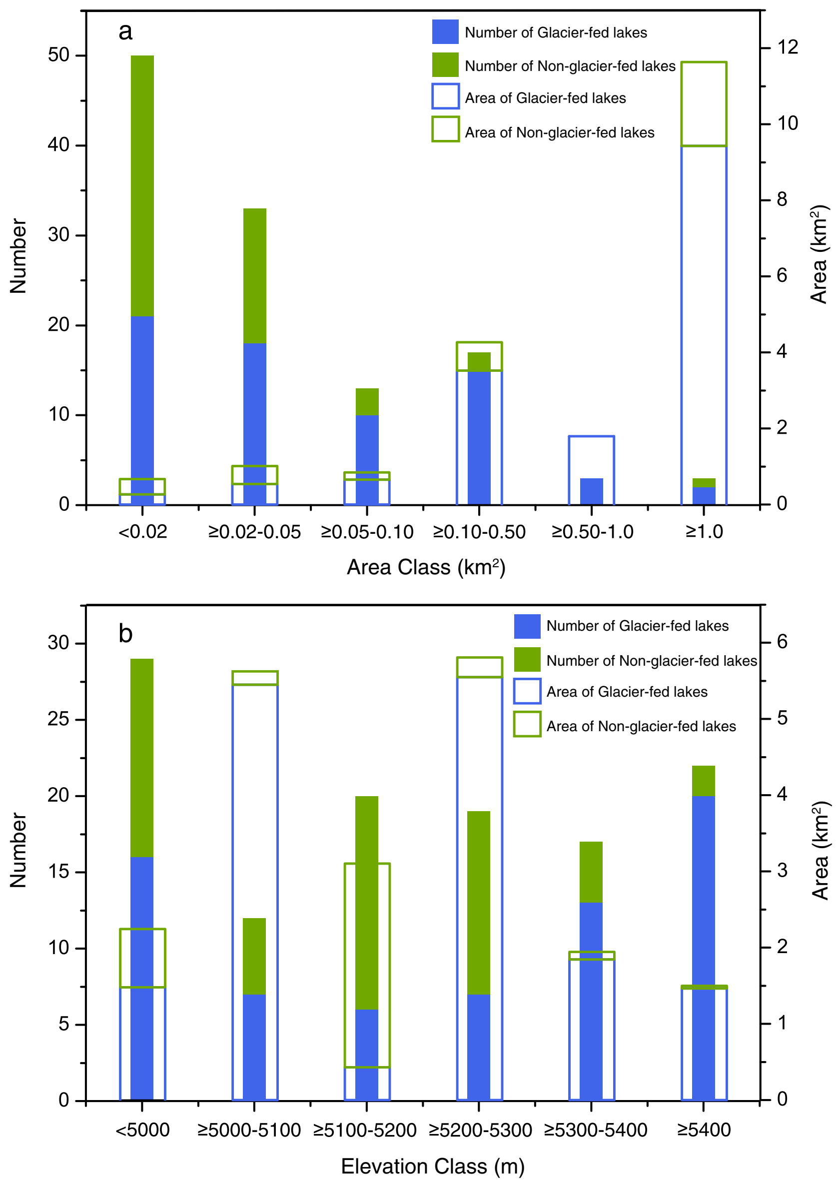

Figure 2. Distribution of glacial lakes according to their (a) area class and (b) elevation class

significantly increased during two phases), shrinking lakes (lake area significantly decreased during two phases) and lakes without significant change (the change of lake area is within the uncertainty interval). A large number of glacier-fed lakes (83%) exhibited continuous growth during the observation period (Figure 3). As for the non-glacier-fed lakes, 20–40% shrank over the different periods. Some lakes that could not be found in

Table III. Summary of lake statistics

Lake type	N	A (km^2)	A_{max} (km^2)	A_{mean} (km^2)	A_{med} (km^2)	Z_{max} (m)	Z_{min} (m)	Z_{mean} (m)	Z_{med} (m)
Glacier-fed lakes	69	16.22	4.83	0.24	0.04	5857	4380	5192	5245
Non-glacier-fed lakes	50	4.01	2.21	0.08	0.02	5524	4120	5027	5171

N, number; A, area; Z, elevation. The subscripts max, min, mean and med indicate the maximum, minimum, mean and median, respectively.

Table IV. Change of glacial lakes from 1976 to 2010

	Number				Area (km^2)				Rate of expansion (km^2 year^{-1})			
Lake type	1976	1991	2000	2010	1976	1991	2000	2010	1976–1991	1991–2000	2000–2010	1976–2010
Glacier-fed lakes	33	36	44	49	7.18	9.50	12.06	15.95	0.15	0.28	0.39	0.26
Non-glacier-fed lakes	19	19	19	20	3.50	3.65	3.61	3.60	0.01	−0.004	−0.001	0.003
Total	52	55	63	69	10.68	13.15	15.67	19.55	0.16	0.28	0.39	0.26

Note that we only summarize the glacial lakes with areas larger than 0.02 km^2.

the 1976 images appeared in the 2010 Landsat images, although we are aware that some tiny and small glacial lakes were undetectable in the Landsat MSS images because of poor image resolution. With only one exception, the emerging lakes in the Poiqu River basin were all glacier-fed lakes.

Concerning the rapid expansion of glacial lakes in the study area, Figure 4 depicts a few examples of rapidly developing lakes, all of which are glacier-fed lakes. Over the last 34 years, the surfaces of these glacial lakes all exhibited continuous growth, and the rate of enlargement appears to have accelerated in the past decade. These glacial lakes all expanded towards the direction of their mother glaciers, or opposite their outlets (Figure 4), most likely because the retreating mother glacier provides space for the glacial lake to expand. Catastrophic drainages of these five lakes occurred in Cirenmaco and Jialongco, and outburst floods have caused severe damage to downstream areas.

Potentially dangerous glacial lakes

We have evaluated the degree of danger for all glacier-fed lakes in the Poiqu River basin (Figure 5), considering almost all of the glacier-fed lakes are moraine dammed with surface drainage and thus are prone to outburst. Of the 69 glacier-fed lakes studied, we identified seven lakes as being prone to outburst according to our method (lakes with an asterisk marked in Table II, Figure 5). Close study of most of the potentially dangerous glacial lakes showed that they are very close to or directly connected to the glacial tongue of the mother glacier. The potentially dangerous glacial lakes were also primarily characterized by rapid areal expansion, e.g. Galongco (no. 14), Gangxico (no. 27), Youmojianco (no. 30) and Cirenmaco (no. 42) (Figure 4).

Because Zhangmu has become the busiest port on the Chinese border and infrastructure development has taken place in the river valley (Shrestha *et al.*, 2010), GLOF hazard assessment has therefore become an important need in the basin. As a preliminary result, the potentially dangerous glacial lakes listed here can be treated as a priority for further assessment, e.g. field-based and modelling-based studies.

DISCUSSION

Linkages to climatic forcing and glacier fluctuations

The evolution of glacial lakes, which formed under certain topographic conditions, has a close relationship with climate change (Wang *et al.*, 2013b). We used the meteorological data recorded at Nyalam station (85°56′, 28°11′, 3810 m a.s.l., see location in Figure 1) to analyse the fluctuations of mean annual temperature and annual precipitation. Figure 6 shows the variations of mean annual temperature and annual precipitation during 1970–2012 recorded at Nyalam station. The mean annual air temperature at Nyalam station documents a significant rise at a rate of 0.24 °C/10a during 1970–2012 ($R^2 = 0.37$, $P < 0.001$). In contrast, annual precipitation recorded at Nyalam station shows a slight decrease during the same period, although the trend was not statistically significant at the 5% level.

In the case of glacier-fed lakes, temperature change affects the mass balance of the mother glacier, whereas precipitation change affects both the mother glacier's mass balance and incoming water to the lake. Actually,

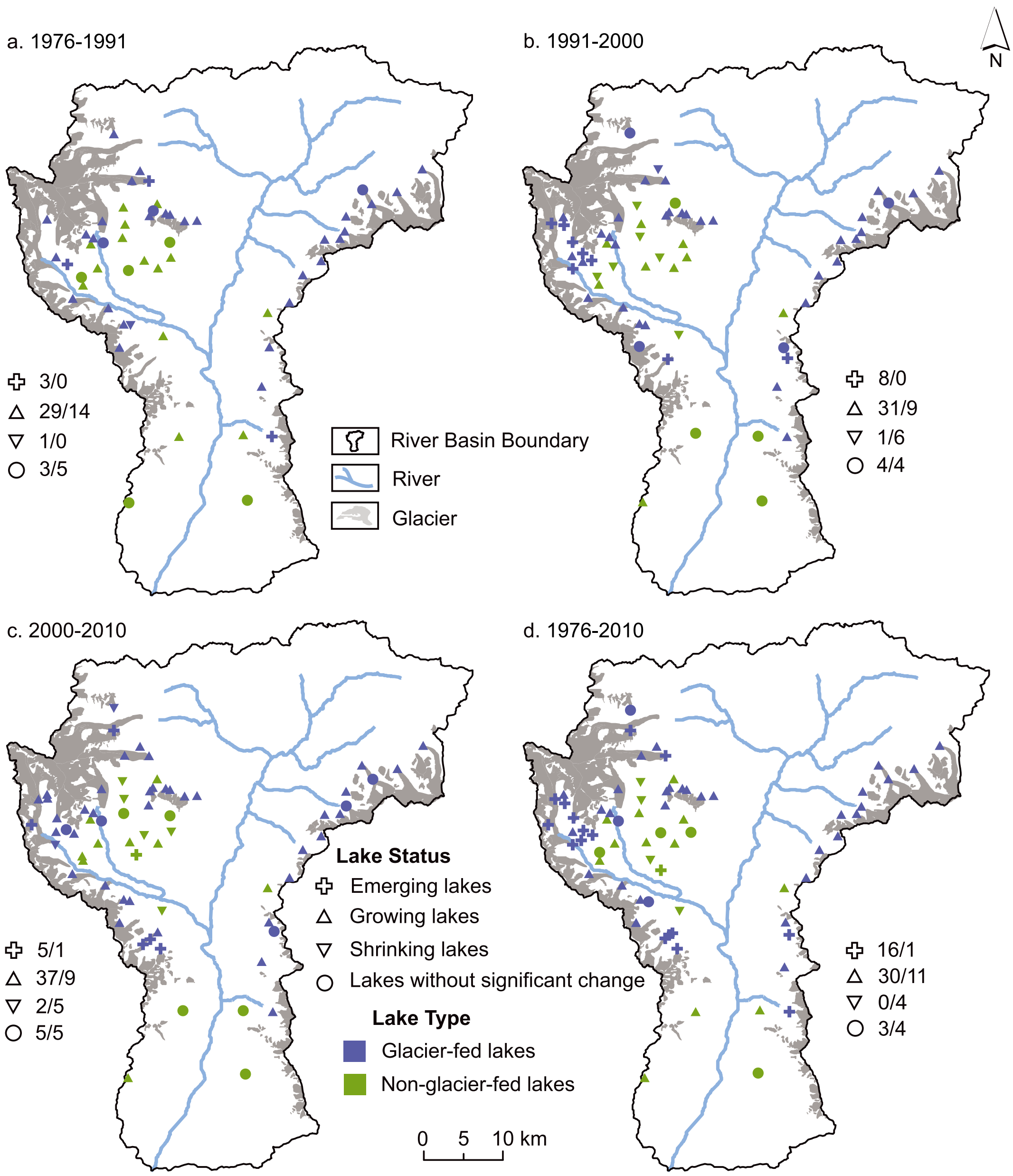

Figure 3. The status of glacial lakes during different periods from 1976 to 2010. Also shown is the number of glacial lakes with different statuses (glacier-fed lakes/non-glacier-fed lakes). Emerging lakes: $A_1 < 0.02\,\text{km}^2$, $A_2 \geq 0.02\,\text{km}^2$; growing lakes: $A_2 > A_1$ and $|A_2 - A_1| >$ uncertainty interval (km^2); shrinking lakes: $A_2 < A_1$ and $|A_2 - A_1| >$ uncertainty interval (km^2); lakes without significant change: $|A_2 - A_1| \leq$ uncertainty interval (km^2), where A_1 and A_2 are the lake area in phases 1 and 2

almost all glacier-fed lakes have surface drainage and water overflows from the terminal moraine outlet, so it is not necessary to consider the effect of precipitation as incoming water to the lake. From Figure 4, the lake shore at the outlet (terminal moraine) side shows no change, so one can estimate that lake water has been overflowing from the outlet and incoming water does not affect the expansion of such lakes. Thus, we estimate that glacier-fed lakes expand mostly by glacier retreat controlled by climate change.

Therefore, we also prepared glacier inventories for each phase and analysed the relationship between glaciers and glacier-fed lakes quantitatively. Figure 6 shows the glacier areas in 1976 ($249.8\,\text{km}^2$), 1991 ($233.1\,\text{km}^2$), 2000 ($221.5\,\text{km}^2$) and 2010 ($203.4\,\text{km}^2$), respectively. From 1976 to 2010, the area of glacier-fed lakes in our study area increased by 122.1%, whereas the glacier area shrank by 18.6%. The expansion of glacier-fed lakes corresponds well with the shrinkage of glaciers during the entire study period. Increasing ablation rate induced by

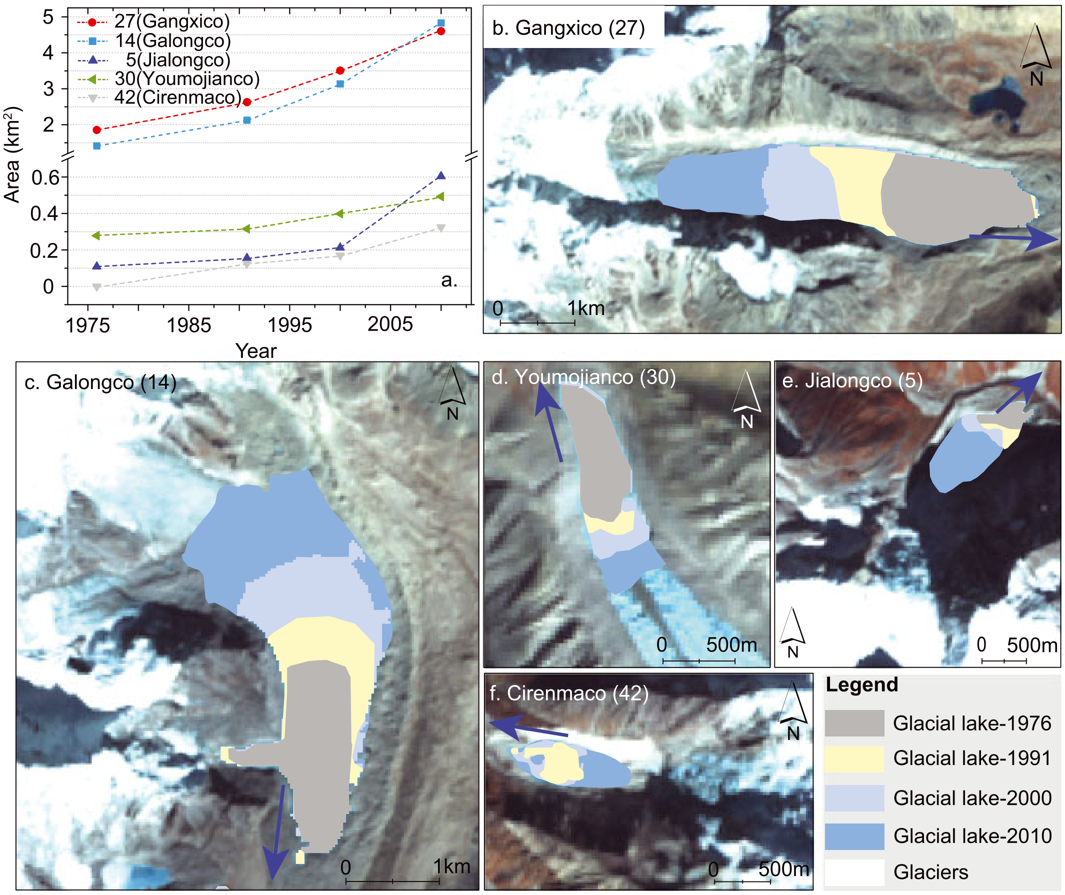

Figure 4. Temporal growth of five glacial lakes in the Poiqu River basin during 1976–2010. The arrows in panels b–f indicate the draining direction of the lakes. The glacial lakes all expanded towards the direction of their mother glacier, or opposite to their outlet. See lakes' location in Figure 5

rising temperature was the main climatic forcing to glacier shrinkage. Additionally, glacial lakes can also impact glacier retreat. The enhanced melting of ice at submerged glacier fronts through circulating warm lake water can accelerate glacier retreat (Kääb and Haeberli, 2001). With the retreating and melting of glacier ice, glacier-fed lakes may expand to flat areas left by retreating glaciers (Wang *et al*., 2011b).

Characteristics of glacial lake distribution

The new 2010 inventory of glacial lakes reveals that the Poiqu River basin is a hot spot for glacial lake distribution. Such lake distribution studies have already been performed in other regions along the Hindu Kush Himalaya (HKH). Gardelle *et al*. (2011) selected seven sites from western to eastern HKH to conduct a preliminary regional assessment of glacial lake distribution. The results revealed that the lake area per glacier area (total glacial lake area/overall glacierized area within each study region) in the eastern part of the HKH was two orders of magnitude larger than that in the western part, indicating that glacial lakes in the eastern HKH are more numerous (or larger) than in the west.

To compare the glacial lakes of the Poiqu River basin with those of other regions throughout the HKH, we calculated the lake area per glacier area for the Poiqu River basin and compared the results with those of other regions characterized by Gardelle *et al*. (2011). Of all the regions analysed, the Poiqu River basin exhibited the largest lake area per glacier area (Figure 7). Because the Poiqu River basin is also located in the eastern part of HKH, our results confirm that eastern parts of HKH are characterized by a greater presence of glacial lakes than their western counterparts.

Differences in the glacial lake density between the eastern and western HKH appear to be primarily a function of climate regimes and the status of glaciers. The eastern climate is dominated by the Indian monsoon and is more humid than the arid and semi-arid western part, where the climate is controlled by the westerlies (Yao *et al*., 2012). Moreover, systematic differences in glacier status from east to west, as reported in recent studies (e.g. Fujita and Nuimura, 2011; Scherler *et al*.,

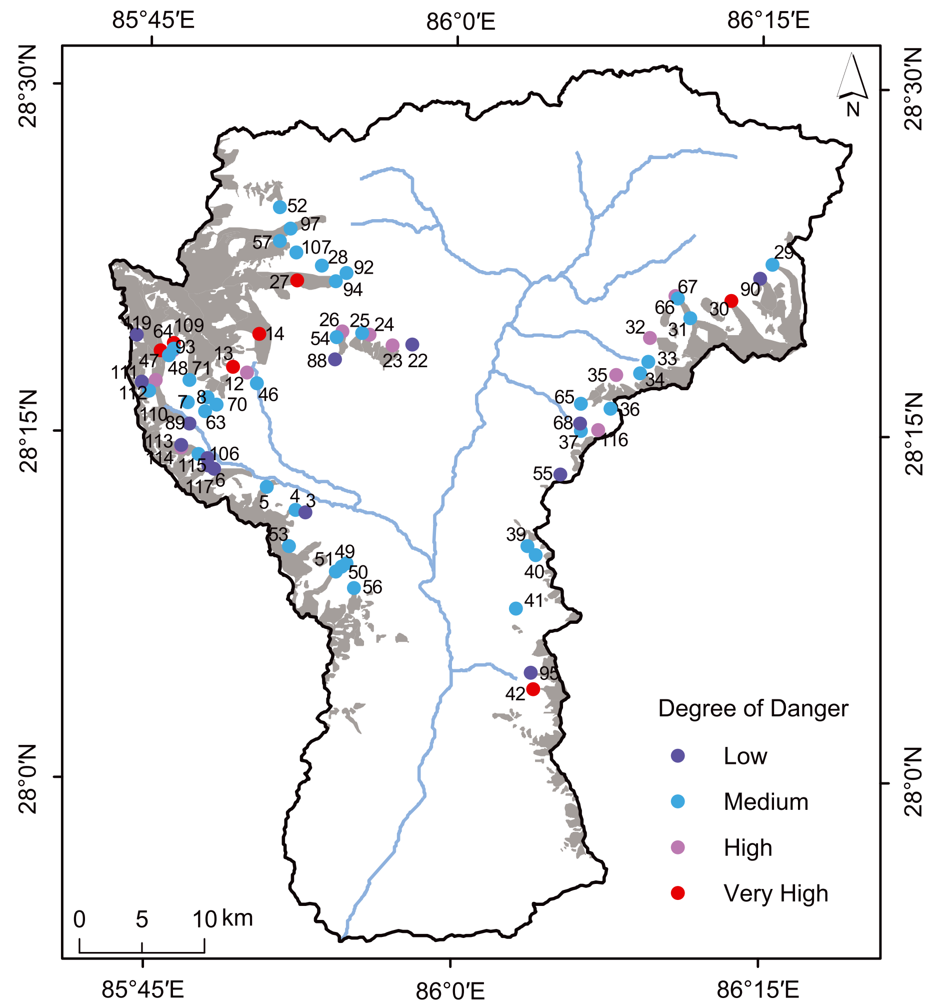

Figure 5. Potentially dangerous glacial lakes identified in the study area. Note: Our method only considers the scenario of lake outburst as a consequence of impact waves from ice avalanches

2011; Bolch *et al.*, 2012; Gardelle *et al.*, 2012; Yao *et al.*, 2012), indicate that the majority of Himalayan glaciers are losing mass, whereas Karakoram glaciers exhibit an anomalous stability or mass gain (Kääb *et al.*, 2012). A positive correlation between glacier retreat and the formation or evolution of glacial lakes can be expected at least on a qualitative level (Mergili *et al.*, 2013), because glacial lakes typically form in the foreland left by retreating glaciers. Therefore, the eastern parts of the HKH, where the climate is humid and glaciers are retreating, can produce more glacial lakes than the western parts.

Contrasting patterns of glacier-fed lakes and non-glacier-fed lakes

As previously mentioned (also in Table IV), the mean expansion rates of different types of glacial lakes in the Poiqu River basin exhibit contrasting patterns: glacier-fed lakes significantly expanded by 122.1% from 1976 to 2010, whereas non-glacier-fed lakes remained stable (+2.8%). This contrast in glacial lake growth within a particular climate zone could be attributed to the impacts of mother glaciers (Gardelle *et al.*, 2011; Salerno *et al.*, 2012). Compared with non-glacier-fed lakes, glacier-fed lakes are influenced by glacial retreat and melting (e.g. subaerial melting, water-line melting and ice calving; cf. Gardelle *et al.* 2011). Thus, with mother glacier retreat and melting, glacier-fed lakes will receive a larger area to expand, which typically results in lake expansion. The contrasting patterns of glacier-fed lakes and non-glacier-fed lakes verify the importance of glacial retreat with regard to lake expansion on a regional scale.

Non-glacier-fed lakes in the study area were stable as a whole, indicating that hydrological processes (e.g. inflow, precipitation, evaporation and runoff, if applicable) were in a state of dynamic balance. As for the individual lakes in the category, Salerno *et al.* (2012) found that their

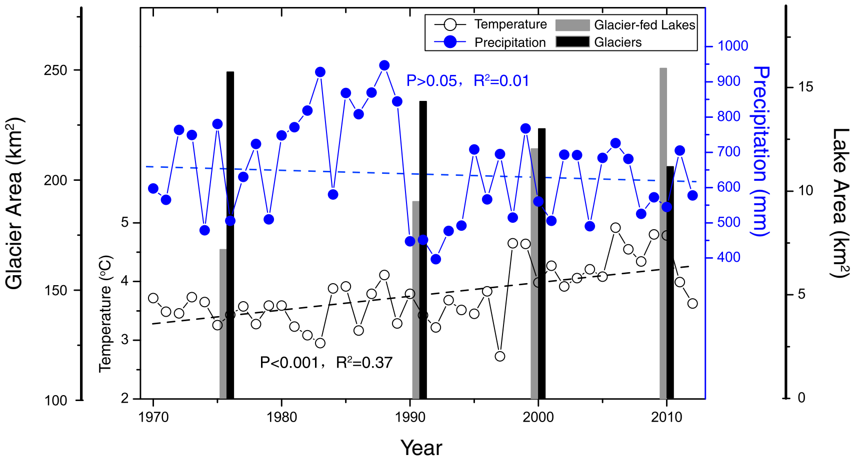

Figure 6. Variations of mean annual temperature and annual precipitation during 1970–2012 recorded at Nyalam station corresponding to the areas of glaciers and glacier-fed lakes in the Poiqu River basin

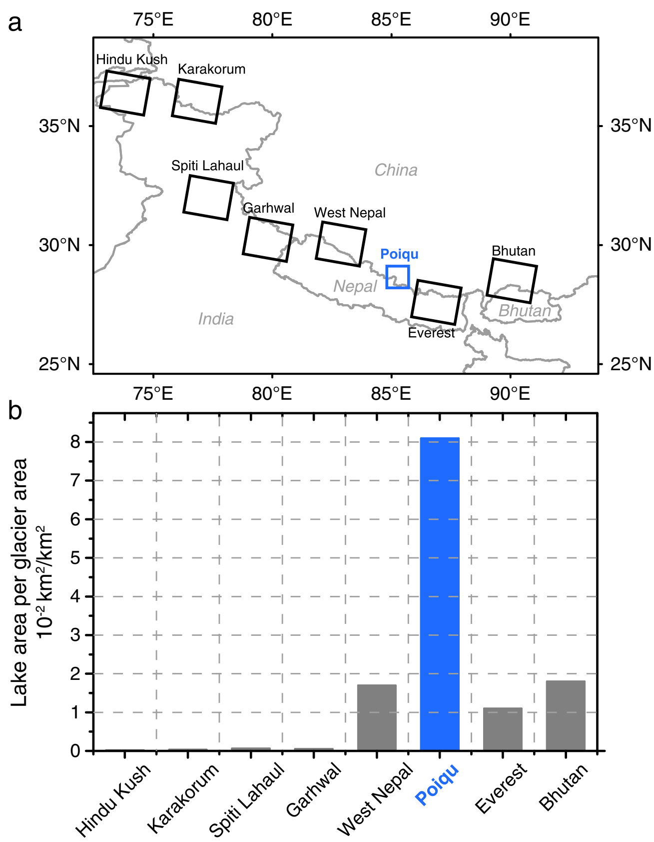

Figure 7. Comparison of glacial lake density in the Poiqu River basin with other regions along Hindu Kush Himalayas. (a) Locations of the study sites for comparison; (b) the lake area per glacier area for the study sites

surface areas were correlated with the dimensions of their catchment. With a limited number of non-glacier-fed lakes in the Poiqu River basin, we have confirmed this observation. Figure 8 shows that the surface areas of non-glacier-fed lakes are significantly correlated ($R^2 = 0.65$, $P < 0.001$) with the areas of their drainage basins. The positive correlation between lake area and catchment size is simply caused by the fact that areas with large catchments are more likely flat and therefore suitable for lake development. However, for the glacier-fed lakes, no correlation is found between lake area and its catchment size (Figure 8, $R^2 = 0.08$, $P > 0.05$). That is

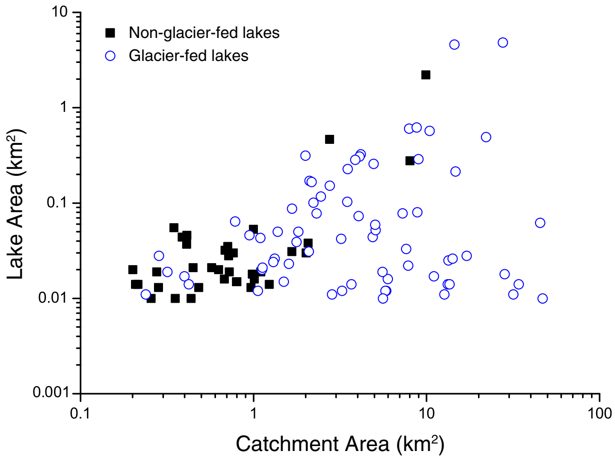

Figure 8. Relationship between the lake area and its catchment area for glacier-fed lakes and non-glacier-fed lakes

because glacier retreat can also impact the evolution of the glacier-fed lakes.

CONCLUSION

In this study, we prepared an updated glacial lake inventory for the Poiqu River basin using Landsat images and subsequently analysed the development of glacial lakes from 1976 to 2010. Our results show that glacier-fed lakes that are connected to glacial watersheds and non-glacier-fed lakes that are not connected to glacial watersheds exhibited contrasting evolution patterns, with the former expanding significantly whereas the latter remaining stable as a whole. Rapid expansion of glacier-fed lakes corresponds well with glacier shrinkage. This suggests that lakes with glaciers within their catchments are benefiting from glacial melting.

The glacial lake inventory presented here can be used as a basis for further hazard assessment of the glacial lakes. The whole dataset will be freely available at the Third Pole Environment Database (http://www.tpedatabase.cn/), established by the Institute of Tibetan Plateau Research Chinese Academy of Sciences, for future studies.

ACKNOWLEDGEMENTS

We would like to thank Wilfried Haeberli, Martin Mergili and the editor Doerthe Tetzlaff for their valuable comments and recommendations, which helped to improve the manuscript. We also thank Betsy Armstrong for polishing the English of the manuscript. This work was supported by the Strategic Priority Research Program (XDB01020300) of the Chinese Academy of Sciences. Landsat images were provided by the International Scientific and Technical Data Mirror Site, Computer Network Information Center, Chinese Academy of Sciences. Topographic maps and DEMs were supplied by the National Geomatics Center of China. Meteorological data from the Nyalam station were kindly supplied by the China Meteorological Data Sharing Service System.

REFERENCES

Bajracharya S, Mool P, Shrestha B. 2007. *Impact of Climate Change on Himalayan Glacier and Glacial Lakes: Case Studies on GLOF and Associated Hazards in Nepal and Bhutan*. ICIMOD: Kathmandu.

Benn DI, Bolch T, Hands K, Gulley J, Luckman A, Nicholson LI, Quincey D, Thompson S, Toumi R, Wiseman S. 2012. Response of debris-covered glaciers in the Mount Everest region to recent warming, and implications for outburst flood hazards. *Earth-Science Reviews* **114**: 156–174. doi:10.1016/j.earscirev.2012.03.008

Bhambri R, Bolch T. 2009. Glacier mapping: a review with special reference to the Indian Himalayas. *Progress in Physical Geography* **33**: 672–704. doi:10.1177/0309133309348112

Bolch T, Kulkarni A, Kääb A, Huggel C, Paul F, Cogley JG, Frey H, Kargel JS, Fujita K, Scheel M, Bajracharya S, Stoffel M. 2012. The state and fate of Himalayan glaciers. *Science* **336**: 310–314. doi:10.1126/science.1215828

Bolch T, Peters J, Yegorov A, Pradhan B, Buchroithner M, Blagoveshchensky V. 2011. Identification of potentially dangerous glacial lakes in the northern Tien Shan. *Natural Hazards* **59**: 1691–1714. doi:10.1007/s11069-011-9860-2

Chen XQ, Cui P, Li Y, Yang Z, Qi YQ. 2007a. Changes in glacial lakes and glaciers of post-1986 in the Poiqu River basin, Nyalam, Xizang (Tibet). *Geomorphology* **88**: 298–311. doi:10.1016/j.geomorph.2006.11.012

Chen XQ, Cui P, Yang Z, Qi YQ. 2007b. Risk assessment of glacial lake outburst in the Poiqu River Basin of Tibet Autonomous Region. *Journal of Glaciology and Geocryology* **29**: 509–516.

Ding YJ, Liu JS. 1992. Glacier lake outburst flood disasters in China. *Annals of Glaciology* **16**: 180–184.

Emmer A, Vilímek V. 2013. Review Article: lake and breach hazard assessment for moraine-dammed lakes: an example from the Cordillera Blanca (Peru). *Natural Hazards and Earth System Sciences* **13**: 1551–1565. doi:10.5194/nhess-13-1551-2013

Frey H, Haeberli W, Linsbauer A, Huggel C, Paul F. 2010. A multi-level strategy for anticipating future glacier lake formation and associated hazard potentials. *Natural Hazards and Earth System Sciences* **10**: 339–352. doi:10.5194/nhess-10-339-2010

Fujita K, Nuimura T. 2011. Spatially heterogeneous wastage of Himalayan glaciers. *Proceedings of the National Academy of Sciences of the United States of America* **108**: 14011–14014. doi:10.1073/pnas.1106242108

Fujita K, Sakai A, Nuimura T, Yamaguchi S, Sharma RR. 2009. Recent changes in Imja Glacial Lake and its damming moraine in the Nepal Himalaya revealed by in situ surveys and multi-temporal ASTER imagery. *Environmental Research Letters* **4**: doi:10.1088/1748-9326/4/4/045205

Fujita K, Sakai A, Takenaka S, Nuimura T, Surazakov AB, Sawagaki T, Yamanokuchi T. 2013. Potential flood volume of Himalayan glacial lakes. *Natural Hazards and Earth System Sciences* **13**: 1827–1839. doi:10.5194/nhess-13-1827-2013

Fujita K, Suzuki R, Nuimura T, Sakai A. 2008. Performance of ASTER and SRTM DEMs, and their potential for assessing glacial lakes in the Lunana region, Bhutan Himalaya. *Journal of Glaciology* **54**: 220–228. doi:10.3189/002214308784886162

Gardelle J, Arnaud Y, Berthier E. 2011. Contrasted evolution of glacial lakes along the Hindu Kush Himalaya mountain range between 1990 and 2009. *Global and Planetary Change* **75**: 47–55. doi:10.1016/j.gloplacha.2010.10.003

Gardelle, J., Berthier, E., Arnaud, Y., 2012. Slight mass gain of Karakoram glaciers in the early twenty-first century. *Nature Geoscience* **5**, 322–325. doi:10.1038/ngeo1450

Gardner AS, Moholdt G, Cogley JG, Wouters B, Arendt AA, Wahr J, Berthier E, Hock R, Pfeffer WT, Kaser G, Ligtenberg SRM, Bolch T, Sharp MJ, Hagen JO, van den Broeke MR, Paul F. 2013. A reconciled estimate of glacier contributions to sea level rise: 2003 to 2009. *Science* **340**: 852–857. doi:10.1126/science.1234532

Gruber FE, Mergili M. 2013. Regional-scale analysis of high-mountain multi-hazard and risk indicators in the Pamir (Tajikistan) with GRASS GIS. *Natural Hazards and Earth System Sciences* **13**: 2779–2796. doi:10.5194/nhess-13-2779-2013

Haeberli W. 2013. Mountain permafrost – research frontiers and a special long-term challenge. *Cold Regions Science and Technology* **96**: 71–76. doi:10.1016/j.coldregions.2013.02.004

Hall DK, Bayr KJ, Schoner W, Bindschadler RA, Chien JYL. 2003. Consideration of the errors inherent in mapping historical glacier positions in Austria from the ground and space (1893–2001). *Remote Sensing of Environment* **86**: 566–577. doi:10.1016/s0034-4257(03)00134-2

Huggel C, Haeberli W, Kääb A, Bieri D, Richardson S. 2004. An assessment procedure for glacial hazards in the Swiss Alps. *Canadian Geotechnical Journal* **41**: 1068–1083. doi:10.1139/T04-053

Huggel C, Kääb A, Haeberli W, Teysseire P, Paul F. 2002. Remote sensing based assessment of hazards from glacier lake outbursts: a case study in the Swiss Alps. *Canadian Geotechnical Journal* **39**: 316–330. doi:10.1139/T01-099

Immerzeel WW, van Beek LPH, Bierkens MFP. 2010. Climate change will affect the Asian water towers. *Science* **328**: 1382–1385. doi:10.1126/science.1183188

Jacob T, Wahr J, Pfeffer WT, Swenson S. 2012. Recent contributions of glaciers and ice caps to sea level rise. *Nature* **482**: 514–518. doi:10.1038/nature10847

Kääb A, Berthier E, Nuth C, Gardelle J, Arnaud Y. 2012. Contrasting patterns of early twenty-first-century glacier mass change in the Himalayas. *Nature* **488**: 495–498. doi:10.1038/nature11324

Kääb A, Haeberli W. 2001. Evolution of a high-mountain thermokarst lake in the Swiss Alps. *Arctic, Antarctic and Alpine Research* **33/4**: 385–390.

Kääb A, Huggel C, Fischer L, Guex S, Paul F, Roer I, Salzmann N, Schlaefli S, Schmutz K, Schneider D, Strozzi T, Weidmann Y. 2005. Remote sensing of glacier- and permafrost-related hazards in high mountains: an overview. *Natural Hazards and Earth System Sciences* **5**: 527–554. doi:10.5194/nhess-5-527-2005

Komori J. 2008. Recent expansions of glacial lakes in the Bhutan Himalayas. *Quaternary International* **184**: 177–186. doi:10.1016/j.quaint.2007.09.012

Lü RR. 1999. *Debris Flow and Environment in Tibet*. Chengdu Science and Technology University Press: Chengdu, China.

Li JL, Sheng YW. 2012. An automated scheme for glacial lake dynamics mapping using Landsat imagery and digital elevation models: a case study in the Himalayas. *International Journal of Remote Sensing* **33**: 5194–5213. doi:10.1080/01431161.2012.657370

Liu CH, Sharmal CK. 1988. *Report on First Expedition to Glaciers and Glacier Lakes in the Pumqu (Arun) and Poiqu (Bhote-Sun Kosi) River Basins, Xizang (Tibet), China*. Science Press: Beijing.

McKillop RJ, Clague JJ. 2007a. A procedure for making objective preliminary assessments of outburst flood hazard from moraine-dammed lakes in southwestern British Columbia. *Natural Hazards* **41**: 131–157. doi:10.1007/s11069-006-9028-7

McKillop RJ, Clague JJ. 2007b. Statistical, remote sensing-based approach for estimating the probability of catastrophic drainage from moraine-dammed lakes in Southwestern British Columbia. *Global and Planetary Change* **56**: 153–171. doi:10.1016/j.gloplacha.2006.07.004

Mergili M, Müller JP, Schneider JF. 2013. Spatio-temporal development of high-mountain lakes in the headwaters of the Amu Darya River (Central Asia). *Global and Planetary Change* **107**: 13–24. doi:10.1016/j.gloplacha.2013.04.001

Mergili M, Schneider JF. 2011. Regional-scale analysis of lake outburst hazards in the southwestern Pamir, Tajikistan, based on remote sensing and GIS. *Natural Hazards and Earth System Sciences* **11**: 1447–1462. doi:10.5194/nhess-11-1447-2011

Nayar A. 2009. Climate: when the ice melts. *Nature* **461**: 1042–1046.

Nie Y, Liu Q, Liu S. 2013. Glacial lake expansion in the Central Himalayas by Landsat images, 1990–2010. *PLoS ONE* **8**: e83973. doi:10.1371/journal.pone.0083973

Paul F, Kaab A, Maisch M, Kellenberger T, Haeberli W. 2002. The new remote-sensing-derived swiss glacier inventory: I. Methods. *Annals of Glaciology* **34**: 355–361. doi:10.3189/172756402781817941

Quincey DJ, Richardson SD, Luckman A, Lucas RM, Reynolds JM, Hambrey MJ, Glasser NF. 2007. Early recognition of glacial lake hazards in the Himalaya using remote sensing datasets. *Global and Planetary Change* **56**: 137–152. doi:10.1016/j.gloplacha.2006.07.013

Raj KBG, Remya SN, Kumar KV. 2013. Remote sensing-based hazard assessment of glacial lakes in Sikkim Himalaya. *Current Science* **104**: 359–364.

Richardson SD, Reynolds JM. 2000. An overview of glacial hazards in the Himalayas. *Quaternary International* **65–66**: 31–47. doi:10.1016/S1040-6182(99)00035-X

Sakai A, Fujita K. 2010. Formation conditions of supraglacial lakes on debris-covered glaciers in the Himalaya. *Journal of Glaciology* **56**: 177–181. doi:10.3189/002214310791190785

Salerno F, Thakuri S, D'Agata C, Smiraglia C, Manfredi EC, Viviano G, Tartari G. 2012. Glacial lake distribution in the Mount Everest region: uncertainty of measurement and conditions of formation. *Global and Planetary Change* **92–93**: 30–39. doi:10.1016/j.gloplacha.2012.04.001

Scherler D, Bookhagen B, Strecker MR. 2011. Spatially variable response of Himalayan glaciers to climate change affected by debris cover. *Nature Geoscience* **4**: 156–159. doi:10.1038/ngeo1068

Shrestha AB, Eriksson M, Mool P, Ghimire P, Mishra B, Khanal NR. 2010. Glacial lake outburst flood risk assessment of Sun Koshi basin, Nepal. *Geomatics Natural Hazards & Risk* **1**: 157–169. doi:10.1080/19475701003668968

Sorg A, Bolch T, Stoffel M, Solomina O, Beniston M. 2012. Climate change impacts on glaciers and runoff in Tien Shan (Central Asia). *Nature Climate Change* **2**: 725–731. doi:10.1038/nclimate1592

Wang WC, Yang XX, Yao TD. 2012a. Evaluation of ASTER GDEM and SRTM and their suitability in hydraulic modelling of a glacial lake outburst flood in southeast Tibet. *Hydrological Processes* **26**: 213–225. doi: 10.1002/hyp.8127

Wang WC, Yao TD, Gao Y, Yang XX, Kattel DB. 2011a. A first-order method to identify potentially dangerous glacial lakes in a region of the southeastern Tibetan Plateau. *Mountain Research and Development* **31**: 122–130. doi:10.1659/mrd-journal-d-10-00059.1

Wang WC, Yao TD, Yang W, Joswiak D, Zhu ML. 2012b. Methods for assessing regional glacial lake variation and hazard in the southeastern Tibetan Plateau: a case study from the Boshula mountain range, China. *Environmental Earth Sciences* **67**: 1441–1450. doi:10.1007/s12665-012-1589-z

Wang WC, Yao TD, Yang XX. 2011b. Variations of glacial lakes and glaciers in the Boshula mountain range, southeast Tibet, from the 1970s to 2009. *Annals of Glaciology* **52**: 9–17. doi:10.3189/172756411797252347

Wang X, Ding YJ, Liu SY, Jiang LH, Wu KP, Jiang ZL, Guo WQ. 2013a. Changes of glacial lakes and implications in Tian Shan, central Asia, based on remote sensing data from 1990 to 2010. *Environmental Research Letters* **8**: doi:10.1088/1748-9326/8/4/044052

Wang X, Liu S, Ding Y, Guo W, Jiang Z, Lin J, Han Y. 2012c. An approach for estimating the breach probabilities of moraine-dammed lakes in the Chinese Himalayas using remote-sensing data. *Natural Hazards and Earth System Sciences* **12**: 3109–3122. doi:10.5194/nhess-12-3109-2012

Wang X, Liu S, Guo W, Xu J. 2008. Assessment and simulation of glacier lake outburst floods for Longbasaba and Pida Lakes, China. *Mountain Research and Development* **28**: 310–317. doi:10.1659/mrd.0894

Wang X, Liu SY, Guo WQ, Yao XJ, Jiang ZL, Han YS. 2012d. Using remote sensing data to quantify changes in glacial lakes in the Chinese Himalaya. *Mountain Research and Development* **32**: 203–212. doi:10.1659/mrd-journal-d-11-00044.1

Wang X, Siegert F, Zhou AG, Franke J. 2013b. Glacier and glacial lake changes and their relationship in the context of climate change, Central Tibetan Plateau 1972–2010. *Global and Planetary Change* **111**: 246–257. doi:10.1016/j.gloplacha.2013.09.011.

Worni R, Huggel C, Stoffel M. 2013. Glacial lakes in the Indian Himalayas – from an area-wide glacial lake inventory to on-site and modeling based risk assessment of critical glacial lakes. *Science of the Total Environment*, doi:10.1016/j.scitotenv.2012.11.043.

Xu DM. 1988. Characteristics of debris flow caused by outburst of glacial lake in Boqu River, Xizang, China, 1981. *GeoJournal* **17**: 569–580. doi:10.1007/BF00209443

Yao T, Pu J, Lu A, Wang Y, Yu W. 2007. Recent glacial retreat and its impact on hydrological processes on the Tibetan plateau, China, and surrounding regions. *Arctic Antarctic and Alpine Research* **39**: 642–650.

Yao TD, Thompson L, Yang W, Yu WS, Gao Y, Guo XJ, Yang XX, Duan KQ, Zhao HB, Xu BQ, Pu JC, Lu AX, Xiang Y, Kattel DB, Joswiak D. 2012. Different glacier status with atmospheric circulations in Tibetan Plateau and surroundings. *Nature Climate Change* **2**: 663–667. doi:10.1038/nclimate1580

Yao TD, Wang YQ, Liu SY, Pu JC, Shen YP, Lu AX. 2004. Recent glacial retreat in High Asia in China and its impact on water resource in Northwest China. *Science in China Series D – Earth Sciences* **47**: 1065–1075. doi:10.1360/03yd0256

