Evolution and outburst risk analysis of moraine-dammed lakes in the central Chinese Himalaya

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The recent evolution and outburst risk of two typical moraine-dammed lakes, Galong and Gangxi, central Chinese Himalaya, are analyzed using topographic maps from 1974 and Landsat satellite imagery acquired in 1988, 2000 and 2014. The datasets show the areas of Galong and Gangxi lakes increasing at rates of 0.45 and 0.34 km²/year during the period 1974–2014, an expansion of 501% and 107%, respectively, in the past 41 years, while the areas of the parent glaciers, Reqiang and Jipucong decreased by 44.22% and 37.76%, respectively. The accelerating retreat of the glaciers not only reflects their generally negative mass balance but is consistent with the rapid expansion of the moraine-dammed lakes. When acted upon by external forces such as earthquakes, heavy rainfall, rapid melting of glaciers and dead ice, and snow/ice/rock avalanches, these lakes can become extremely dangerous, easily forming outburst mudslides, which can potentially spread to the Poiqu river basin and develop into cross-border (China and Nepal) GLOF disasters. Therefore, there is an urgent need to strengthen integrated risk management of glacial lake outburst disasters with multiple objectives and modes.

1. Introduction

As global climate warms, glaciers generally shrink and their retreat sometimes allows unstable formation of moraine-dammed lakes. In the Himalaya, moraine-dammed glacial lakes are the dominant type and are the largest lakes in the region. At present, new potentially dangerous glacial lakes (PDGLs) are forming and developing, and existing PDGLs threaten to produce glacial lake outburst floods (GLOFs) throughout high-mountain areas worldwide. GLOFs have hit downstream communities and cities, resulting in great loss of life and the destruction of infrastructure (e.g., roads, bridges, trekking trails), natural resources, valuable property, settlements, farmlands and environment. Most GLOF disasters have been recorded or

reported in British Columbia, Canada; the North Cascades, western North America; the Cordillera Blanca, Peru; central Asia; and the central and eastern Himalaya (Richardson and Reynolds 2000; Mool *et al.* 2001; Kattelmann 2003; Yafazova 2007; Kaltenborn *et al.* 2010; Yao *et al.* 2010; Carey *et al.* 2012; Wang and Zhang 2013, 2014; Liu *et al.* 2014). Mountain communities and cities located in remote areas away from glacial lakes are often within the reach of GLOFs, yet local residents' perception of the threat is relatively weak. Though GLOFs are infrequent, the resulting disasters have caused huge loss of life and property downstream.

According to past records and statistical analyses, since 1935 at least 40 GLOF disasters have occurred in the Chinese Himalaya and Nyainqêntanglha ranges in the Tibetan Plateau,

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Figure 1. Distribution of GLOF disaster sites in Tibet and the location of two typical moraine-dammed lakes (Gangxico and Galongco) in the Poiqu river basin, central Chinese Himalaya.

an incidence of one event every 2 years (figure 1) (Wang and Zhang 2013). Twelve of these disasters occurred in the central Chinese Himalaya, where the most concentrated areas of glacial lakes in the Hindu Kush Himalaya are located (Gardelle *et al.* 2011; Wang and Zhang 2014). Huge numbers of casualties and severe property loss were reported. Trends indicate that both the number and areas of glacial lakes and their influence will continue to increase in the central Himalaya.

With the ongoing development of infrastructure, agriculture and animal husbandry, and tourism activity in the mountain region, the central Himalaya has been spotlighted as being dangerously exposed to GLOF disasters (Kääb *et al.* 2005; Colin 2011). The high vulnerability of inhabitants of the central Himalaya to GLOFs makes it more difficult to alleviate poverty in the region. The threat of GLOFs will require appropriate and continued monitoring well into the 21st century as glacier retreat continues and even accelerates. For these reasons, we performed a case study of typical moraine-dammed lakes on the southeastern slope of Xixiabangma, central Chinese Himalaya, analyzing their evolution and the stability of moraine dams, and climate conditions. Based on this, we also propose a range of measures to prevent and control GLOF disasters.

2. Study area

Gangxico (28°21'N, 85°53'E) and Galongco (28°19'N, 85°51'E) are moraine-dammed lakes ('co' means lake in the Tibetan language), located

at elevations of 5220 m and 5089 m a.s.l. on the southeastern slope of Xixiabangma (Shishapangma) (8021 m), central Chinese Himalaya. The two lakes form the headwater of the Poiqu river and have been identified as the largest and most dangerous lakes in the Poiqu river basin (PRB) (Wang *et al.* 2014) (figure 1). The PRB is one of the headwater tributaries of the Ganges river basin (27°49'–29°05'N, 85°38'–86°57'E). The Poiqu river originates in the central Himalaya and flows southward into Nepal. The basin drainage area is approximately 2160 km². The PRB is affected by the Indian monsoon and experiences high precipitation levels nearly year-round (Xiang *et al.* 2014).

According to monthly data for 1974–2011 obtained from Nyalam meteorological station (3810 m a.s.l.), close to the two moraine-dammed lakes, the mean annual temperature and precipitation are 3.8°C and 650.3 mm, respectively. The mean monthly temperature is below freezing from November through March and above freezing for the rest of the year. The monthly temperature ranges from 10.8°C in July, to –3.4°C in January. The mean monthly precipitation shows a bimodal distribution. The highest rainfall peak appears in September, when the mean precipitation is 87.9 mm/month. Precipitation decreases significantly after October, with the lowest value, 13.0 mm/month, occurring in November. It then decreases gradually until May, when it begins to increase again (figure 2). Additionally, with increasing elevation, temperature and precipitation decrease gradually from south to north. As the areal extent of the Gangxico and Galongco has increased in the past and they are considered more

Figure 2. Mean monthly temperature and precipitation at Nyalam weather station, 1974–2011.

Table 1. Dates of the images used in this study.

Source/sensor	Date	Resolution/scale	Application
Topographic maps	1974	1:50,000	Glacier and glacial lake area
LANDSAT TM/ ETM ⁺ /OLI	1988 2001 2014	30 m	Glacier and glacial lake area, the distance between glacier terminus and nearest lakeshore measurement
ASTER GDEM	2009	30 m	Orthorectification of the images, elevation identification, slop measurement between lake and glacier terminus, and drainage basin identification

dangerous, hence, the two lakes are selected for the present study.

3. Data and method

This study uses Landsat satellite data (Multi-spectral Scanner (MSS)/Thematic Mapper (TM)/Enhanced TM Plus (ETM⁺)/Operational Land Imager (OLI)) as the main source for extracting information about glaciers and glacial lakes. In addition, using the same or similar sensors can reduce the error when extracting information from different types of data (Racoviteanu *et al.* 2010). To avoid cloud and snow cover during the monsoon and ensure minimal snow coverage, we selected three satellite images with less than 5% cloud cover acquired between September and December in 1988, 2000 and 2014 (table 1).

The best-quality image is used as benchmark data for each period, and two or three other images taken at around the same time are used as reference data, which are used to determine the seasonal snow cover (Xiang *et al.* 2014). In this study, we used one 1:50,000 topographic map (produced by the National Geomatics Center of China) and Advanced Spaceborne Thermal Emission and

Reflection Radiometer (ASTER) digital elevation models (DEMs) (table 1; figure 2a). Glacial lake boundaries, distributions and evolutions were investigated using detailed delineations and measurements of satellite-derived imagery. Once the images were rectified, they were further processed before interpretation. Comparisons of the different band combinations showed that the standard false-colour composite (FCC) images made from combining 4, 3, 2 bands were most conducive to identify glacial lake boundaries. When lakes were frozen and snow-covered, visual inspection was necessary to distinguish snowy glacial lakes with the help of the composition images of 7, 5, 2 band composites. In view of the gentle lake surface and steeper hillshade, lakes are assumed to be areas where the slope is less than 10% (Gardelle *et al.* 2011). All images then need to match with ERDAS software, and the 1988, 2000 and 2014 images also require geographic registration to assure overlap with the 2009 ASTER global DEM (GDEM) (<http://data-mirror.csdb.cn>). Based on the above interpretation of the images, glacial lakes were delineated manually from digitized topographic maps and/or FCC satellite images pixel-by-pixel in ArcGIS 9.3 with the help of Google Earth imagery (figure 3). Finally, the vector layers of the three lakes (Gangxico,

Galongco and Gongco) in 1974, 1988, 2000 and 2014 were obtained, and lake type, length, area and altitude were presented by way of eyewitness interpretation and geographic calculation as attribute data (figure 1). The study also used lake area data for 1977, 1984, 1990 and 2003 from Che *et al.* (2005).

Glacial lake outburst is influenced by many variables, such as upstream glacier area and glacier snout steepness; altitude, size and expansion rate of a moraine-dammed lake; distance and slope between lake and glacier terminus; increase in runoff from upstream glaciers; ice/snow/rock avalanches and landslides into the lake; mean slope

Figure 3. Development of Gangxico and Galongco from 1974 to 2014 based on: (a) topographic map (1974), (b) Landsat TM (October 1988), (c) Landsat ETM⁺ (November 2000), (d) Landsat 8 OLI (August 2014), (e) September 2013 field survey and (f) June 2005 field survey by Chen *et al.* (2007). The intact lateral moraine is indicated by yellow arrows. The area of debris-covered stagnant ice is shown by the dashed blue line.

of the moraine dam; moraine height-to-width ratio; lake-dam condition (e.g., dead ice melting or piping of moraine dam); physical surroundings and conditions down-valley; and climate conditions (e.g., relatively high temperature, heavy precipitation, strong winds) (McKillop and Clague 2007; Fujita *et al.* 2008; Bolch *et al.* 2008; ICIMOD 2011). However, the outburst mechanism is mainly focused on two aspects: (1) wave or surge triggered by ice/snow/rock avalanches, landslides and earthquakes through the outlet channel, initiating rapid incision of the moraine, and (2) seepage or piping or enlargement of drainage conduits in the moraine (Kattelmann 2003; Liu *et al.* 2014).

The number of glacial lake outburst samples worldwide is too small to allow outburst probability to be calculated using mathematical statistics or regression analysis. At present, there are no unified criteria to determine a glacial lake outburst. However, some indication of glacial lake outburst probability is provided by certain key factors, of which the upstream glacier area moraine-dammed lake area and its change, distance and slope between lake and mother glacier, the mean slope of the moraine dam, and moraine-dam condition are most often employed by researchers as rough evaluation criteria to determine whether a lake is dangerous or not. Among these factors, the upstream glacier area reflects the area of accumulation and the glacier snout and suggests the magnitude of snow and ice avalanche if it occurs. The moraine-dammed lake area affects the volume of stored water and the maximum outburst flood volume, while the distance and slope between the lake and the glacier terminus and the steepness of the glacier snout determine the scale of snow/ice/rock avalanches that collapse into the lakes from the glacier terminus, and whether the displacement waves from these snow/ice/rock bodies will further trigger an outburst flood (Awal *et al.* 2010; Wang *et al.* 2011; Schaub *et al.* 2013). In the 20 most recently recorded GLOF disasters, 95% of outburst lake areas were more than 0.02 km², and the distance between the lake and the mother glacier terminus was less than 500 m in the Chinese Himalaya. Lake area variations reflect the state of their hydrologic balance to a certain extent. Rapid area changes will upset the hydrologic balance, promoting moraine-dammed lake outburst. The mean slope of the moraine dam dictates the dam's stability (Wang and Zhang 2013). For these reasons, we propose the mother glacier area, the lake area, lake area change, the distance between lake and glacier terminus, mother glacier snout steepness, the slope between lake and glacier, and mean slope and moraine-dam condition of a lake dam to analyze glacial lake potential hazard in our study area.

To analyze climate variability within the study area, daily air temperature and precipitation data since 1974 were obtained from Nyalam station (28°11'N, 85°56'E; 3810 m a.s.l.; figure 1). Climate data were provided by the National Climate Centre of the China Meteorological Administration. From the Nyalam station data, we calculated monthly mean temperature and precipitation by averaging the recorded diurnal temperature and precipitation in the month, and then annual mean temperature and precipitation by averaging the obtained monthly data.

4. Results and analysis

4.1 Glacial lake evolution, 1974–2014

Changes at Gangxico and Galongco have been documented since 1974. The lake areas have been found to be growing rapidly. In 1974, they were 1.67 and 0.88 km², respectively, and by 1990 they had increased to 2.91 and 2.37 km², respectively. In the past 17 years, Gangxico and Galongco areas increased by 74.25% and 169.32%, respectively. In 1974, a small lake appeared on the western shore of Galongco, and it had merged with Galongco by 1988. Since this period, surface expansion of Gangxico and Galongco has persisted. During the period 1990–2000, the two lakes expanded to approximately 3.49 and 3.24 km², at an annual rate of 0.053 and 0.079 km²/year, respectively. From 2000–2014, Gangxico and Galongco expanded further, by 0.08 and 0.14 km²/year to reach 4.633 and 5.295 km². According to the empirical formula by Huggel *et al.* (2002), $V=0.104A^{1.42}$, where V is the lake volume and A is the lake area (m²) as of 2014, Gangxico and Galongco volumes have reached 3.04×10^8 and 3.67×10^8 , respectively (figure 4).

Figure 4 shows that Gangxico and Galongco have increased in area at rates of 0.34 km²/year ($R^2=0.98$, $P<0.001$) and 0.45 km²/year ($R^2=0.95$, $P<0.001$) during the period 1974–2014, an increase of 107% and 501%, respectively in the past 41 years. The increase in lake area is directly related to the decline of the glacier front during the same period. The lake area increase correlates with an increase in volume of the lake basin. Rapid expansion of the lake area increases the likelihood of dam failure, and poses a severe threat to the downstream social economy. Gongco, located between Gangxico and Galongco, is presently not in contact with a glacier and is classified as a 'control lake'. The Gongco area is significantly more stable than those of Galongco and Gangxico, and shows a slight decrease at a rate of 0.14 km²/decade ($R^2=0.35$, $P>0.05$) (figure 4).

Figure 4. The trends of change at Gangxico, Galongco and Gongco during 1974–2014.

4.2 Analysis of glacial lake potential dangerous risk

GLOFs generally represent the highest and most far-reaching glacial risk, with the most serious disaster and damage potential (Richard and Gay 2003). Lü (1999) and Wang *et al.* (2011, 2012a, b) found that moraine-dammed lakes have a much higher risk of outburst when the mother glacier area is more than 1 km², the slope between lake and glacier is more than 17°, the mean slope of the moraine dam is more than 14°, glacier snout steepness is more than 19°, the distance between lake and glacier terminus is less than 300 m, the moraine dam width-to-height ratio is less than 1 and the slope of the downstream face of the moraine dam is more than 20°. Although these thresholds need to be further verified, these extremes at least shows that these lakes with these thresholds have a great or very high outburst risk.

Gangxico and Galongco were originally formed as a result of a valley glacier retreat. They are enclosed by parent glaciers (Reqiang and Jicongpu glaciers; >4.0 km² area), their termini and the end and lateral moraines. Remote images and

photogrammetric mapping show that the two lake surfaces grew at an accelerating rate and the moraine damming of the two lakes consists of typical unconsolidated moraine material. Gangxico is only 100 m from Reqiang glacier terminus, with about 30° steepness. Figure 5 shows the relicts of an ice avalanche body on the lakeshore near Reqiang glacier front. An ice or snow avalanche event will induce a dynamic wave on the lake and is liable to generate a GLOF. The terminal moraine dam of Gangxico is approximately 15–20 m above lake level, with crest width and length of about 20 m and 1000–2000 m, respectively and a dam outside slope of about 20°. The deciding factor for the development of the moraine dam is the presence of buried ice. The degradation of buried ice is accompanied by morainic sediment sliding and falling downslope (Richardson and Reynolds 2000), resulting in the instability and transient lifetime of the current dam. According to fieldwork in 2013, Gangxico has a broad area of stagnant debris-covered ice and a residual ice-free debris area behind the moraine (figure 5), the terminal moraine dam has no outlet and lake water is mainly

Figure 5. The Gangxico moraine dam with superficial outflow (centre). Photo taken by Shijin Wang in September 2013.

discharged in the form of multiple seepage. Accelerating melting of dead ice bodies which constitute the moraine dam can lead directly to dam failure and subsequent rapid water release from the lake. In addition, the downstream bed distributes large moraines and weathered materials, which provide a rich source of material conditions for the formation of glacial lake outburst mudslides.

Galongco, located to the south of Gangxico, is only 200 m from Jipucong glacier tongue, with 20° steepness. Like Gangxico, it has a relatively simple dam structure, but its area and water storage are much larger than those of Gangxico. The south side of the moraine dam at the outlet rises approximately 50 m above the lake surface, and the terminal moraine dam crest width and length are about 20 m and 400–600 m, with a dam outside slope of 25°–30° which is not conducive to the stability of the dam. The stream gradient of the downstream channel is about 200%. The rise in water level has led to the formation of a new small lake connected to the original lake (Chen *et al.* 2007) (figure 3f).

The above analysis indicates that the areas of the two lakes with mother glaciers are more than 4.0 km² and 4.6 km², and that Gangxico and Galongco have expanded by 107% and 501% respectively in the past 41 years. Gangxico is only 100 m from the Reqiang glacier terminus with 30° steepness, while Galongco is about 200 m from Jipucong glacier tongue with 20° steepness. The moraine-dam width-to-height ratio at Gangxico and Galongco is about 1.2 and 0.4, respectively. The overall results show that Gangxico has a high outburst risk, while Galongco has a very high outburst risk. The terminal moraine dams of the two glacial lakes exist in the degradation phenomenon of buried ice. Downstream of the two lakes, there are many

human settlements, bridges and other infrastructure and so the two lakes pose a very high GLOF disaster risk.

5. Discussions

The majority of the world's mountain glaciers have been characterized by an increasingly negative mass balance and consequent glacier shrinkage and glacial lake expansion attributed to rapid climatic warming in recent decades (Dyrugerov 2003; Oerlemans 2005; Kumar and Murugesh Prabhu 2012). In warm conditions, glaciers retreat rapidly and the meltwater supply to glacial lakes increases, resulting in an increasing lake area. In our study area, there is a meteorological station at Nyalam, located on the south slope of Xixiabangma (figure 1). Figure 6 shows that the mean annual air temperature at Nyalam station underwent a significant increase at a rate of 0.4°C/decade during the period 1974–2011 ($R^2=0.55$, $P<0.001$), while annual precipitation shows a slight decrease at a rate of 26.8 mm/decade ($R^2=0.24$, $P>0.05$), although the trend was not statistically significant at the 5% level (figure 6). 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 (Wang *et al.* 2014).

Deglaciation in the central Chinese Himalaya is intensifying in a climate that tends to be relatively dry and warm. During the past decade, the shrinkage of Himalayan glaciers has shown an accelerating trend. This dramatic retreat may result in an increase in the number and area of glacial

Figure 6. Temperature and precipitation change at Nyalam station during 1974–2011.

Table 2. Historical retreat of Jipucong and Reqiang glaciers.

Glacier name	Area (km ²)					Area increase (%)			
	1974	1988	2000	2010	2014	1974–1988	1988–2000	2000–2014	1974–2014
Reqiang	7.44	7.43	5.03	4.46	4.15	−0.08	−11.29	−17.53	−44.22
Jicongpu	7.65	6.84	5.52	5.68	4.76	−10.61	2.97	−13.63	−37.76

lakes, which when they overflow will potentially cause outburst floods with catastrophic impacts on downstream areas. The initiation, formation and development of glacial lakes have a close relationship with changes in glacier extent and volume, because they are fed by meltwater discharge from adjacent or adjoining glaciers. Figure 6 shows that climate conditions in the study area are characteristic of a hot-arid environment, with intensified warming associated with a lower increase in precipitation in the past two decades, resulting in accelerated glacier retreat and glacial lake expansion. Based on the available satellite remote-sensing data and data from topographic maps, we have analyzed the variation of the two parent glaciers (Reqiang and Jipucong glaciers). The results show that these glaciers have undergone a remarkable retreat during the past 41 years. The area of Reqiang and Jipucong glaciers decreased by 44.22% and 37.76%, respectively, from 1974 to 2014, indicating a faster retreat by Reqiang glacier than by Jipucong glacier. It is noteworthy that the magnitude of the two parent glaciers' recession in the 1974–1988 period was smaller than that between 2000 and 2014, in a climatic context of large temperature increase and lower precipitation increase (table 2). The accelerating retreat of the glaciers not only reflects the

generally negative mass balance of glaciers, but is consistent with the rapid expansion of moraine-dammed lakes.

6. Conclusions

In a warming climate, Himalayan glaciers have retreated and thinned rapidly in recent decades, leading to rapid expansion of existing moraine-dammed lakes and a concomitant increase in the threat of glacial lake outburst disasters. Downstream of Gangxico and Galongco, many entities are at high risk in the event of an outburst (e.g., human settlements, telecommunications networks, bridges, rural roads and state roads). When acted upon by external forces such as earthquakes, heavy rainfall, rapid melting of glaciers, snow/ice avalanches, etc., the moraine-dammed lakes can become extremely dangerous, easily forming outburst mudslides, which can potentially spread to the PRB and develop into cross-border disasters.

Given the seriousness of the situation at Galongco and Gangxico, a programme for an early-warning and outburst-risk management system along the downstream valley should be established in the near future (Petrakov *et al.* 2012). It is

extremely difficult to conduct flood drainage and other projects on moraine dams because of the high altitude of lakes, the steep terrain, complex climate conditions and high engineering costs. The reduction of exposure and vulnerability through early warning and prevention would be more realistic given the limited local budget available. There is an urgent need to strengthen the integrated risk management of glacial lake outburst disasters with multiple objectives and modes. Risk management measures should include regular monitoring of the dynamics of glacial lakes, GLOF simulation using hydrodynamic modelling, risk investigation of glacial lakes, the performance of reasonable engineering measures (if necessary, lower the lake level by using an open spillway or reinforce the lake dam), the implementation of a participation mechanism with multiple stakeholders and a community-based disaster risk management mechanism, and the improvement of mass observation and prevention systems and so on (Wang *et al.* 2012a, b). It has important theoretical reference to implement integrated risk management measures for the establishment of disaster prevention and mitigation system.

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References

- Awal R, Nakagawa H, Fujita M, Kawaike K, Baba Y and Zhang H 2010 Experimental study on glacial lake outburst floods due to waves overtopping and erosion of moraine dam; *Ann. Disas. Prev. Inst. Kyoto Univ.* **53** 583–590.
- Bolch T, Buchroithner M F, Peters J, Baessler M and Bajracharya S 2008 Identification of glacier motion and potentially dangerous glacial lakes in the Mt. Everest region/Nepal using spaceborne imagery; *Nat. Hazards Earth Syst. Sci.* **8** 1329–1340.
- Carey M, Huggel C, Bury J, Portocarrero C and Haeberli W 2012 An integrated socio-environmental framework for climate change adaptation and glacier hazard management: Lessons from Lake 513, Cordillera Blanca, Peru; *Clim. Change* **112** 733–767.
- Che T, Li X, Mool P K and Xu J C 2005 Monitoring glaciers and associated glacial lakes on the east slopes of Mount Xixiangma from remote sensing images; *J. Glaciol. Geogr.* **27**(6) 801–805 (in Chinese).
- Chen X Q, Cui P, Li Y, Yang Z and Qi Y Q 2007 Changes in glacial lakes and glaciers of post-1986 in the Poiqu River basin, Nyalam, Xizang (Tibet); *Geomorphology* **88** 298–311.
- Colin A Whiteman 2011 *Cold Region Hazards and Risks*; John Wiley and Sons Publishing.
- Dyrugorov M B 2003 Mountain and sub-polar glaciers show an increase in sensitivity to climatic warming and intensification of the water cycle; *J. Hydrol.* **282**(1–4) 164–176.
- Fujita K, Suzuki R, Nuimura T and Sakai A 2008 Performance of ASTER and SRTM DEMs, and their potential for assessing glacial lakes in the Lunana region, Bhutan Himalaya; *J. Glaciol.* **54**(185) 220–228.
- Gardelle J, Arnaud Y and Berthier E 2011 Contrasted evolution of glacial lakes along the Hindu Kush Himalaya mountain range between 1990 and 2009; *Global Planet. Change* **75** 47–55.
- Huggel C, Kääb A, Haeberli W, Teyssie P and Paul F 2002 Remote sensing based assessment of hazards from glacier lake outbursts: A case study in the Swiss Alps; *Canadian Geotech. J.* **39** 316–330.
- ICIMOD 2011 Glacial lakes and glacial lake outburst floods in Nepal, Kathmandu; ICIMOD.
- Kääb A, Reynolds J M and Haeberli W 2005 Glacier and permafrost hazards in high mountains; In: *Global Change and Mountain Regions (A State of Knowledge Overview)* (eds) Huber U M, Bugmann H K M and Reasoner M A, Springer.
- Kaltenborn B P, Nellesmann C and Vistnes II 2010 High mountain glaciers and climate change – Challenges to human livelihoods and adaptation; Birkeland Trykkeri AS, Norway.
- Kattelmann R 2003 Glacial lake outburst floods in the Nepal Himalaya: A manageable hazard? *Nat. Hazards* **28** 145–154.
- Kumar B and Muruges Prabhu T S 2012 Impacts of climate change: Glacial lake outburst floods (GLOFs); In: *Climate change in Sikkim: Patterns, impacts and initiatives*, Information and Public Relations Department, Government of Sikkim, Gangtok.
- Liu J J, Cheng Z L and Su C S 2014 The relationship between air temperature fluctuation and glacial lake outburst floods in Tibet, China; *Quat. Int.* **321** 78–87.
- Lü R 1999 Debris flow and environment in Tibet; China Chengdu Science and Technology University Press (in Chinese).
- McKillop R J and Clague J J 2007 Statistical, remote sensing-based approach for estimating the probability of catastrophic drainage from moraine-dammed lakes in southwestern British Columbia; *Global Planet. Change* **56** 153–171.
- Mool P K, Bajracharya S R and Joshi S P 2001 *Inventory of Glaciers, Glacial Lakes and Glacial Lake Outburst Floods: Monitoring and Early Warning Systems in the Hindu Kush-Himalayan Region*, International Centre for Integrated Mountain Development (ICIMOD) Kathmandu, NP, Kathmandu.
- Oerlemans J 2005 Extracting a climate signal from 169 glacier records; *Science* **308** 675–677.
- Petrakov D A, Tutubalina O V, Aleinikov A A, Chernomoretz S S, Evans S G, Kidyaeva V M, Krylenko I N, Norin S V, Shakhmina M S and Seynova I B 2012 Monitoring of Bashkara Glacier lakes (Central Caucasus, Russia) and modeling of their potential outburst; *Nat. Hazards* **61** 1293–1316.
- Racoviteanu A E, Paul F, Raup B, Khalsa S J S and Armstrong R 2010 Challenges and recommendations in mapping of glacier parameters from space: Results of the 2008 Global Land Ice Measurements from Space (GLIMS)

- workshop, Boulder, Colorado, USA; *Ann. Glaciol.* **50**(53) 53–69.
- Richard D and Gay M 2003 Glaciorisk – Survey and prevention of extreme glaciological hazards in European mountainous regions; EVG1 2000 00512 Final report (01.01.2001e31.12.2003), <http://glaciorisk.grenoble.cemagref.fr>.
- Richardson S D and Reynolds J M 2000 An overview of glacial hazards in the Himalaya; *Quat. Int.* **65–66** 31–47.
- Schaub Y, Haeberli W, Huggel C, Künzler M and Bründl M 2013 Landslides and new lakes in deglaciating areas: A risk management framework; The Second World Landslide Forum (eds) Margottini *et al.*, *Landslide Science and Practice* **7** 31–38, doi: [10.1007/978-3-642-31313-4_5](https://doi.org/10.1007/978-3-642-31313-4_5).
- Wang S J and Zhang T 2013 Glacial lakes change and current status in the central Chinese Himalaya from 1990 to 2010; *J. Appl. Remote Sens.* **7**(1) 073459, doi: [10.1117/1.JRS.7.073459](https://doi.org/10.1117/1.JRS.7.073459).
- Wang S J and Zhang T 2014 Spatially change detection of glacial lakes in the Koshi River Basin, the central Himalaya; *Environ. Earth Sci.*, doi: [10.1007/s12665-014-3338-y](https://doi.org/10.1007/s12665-014-3338-y).
- Wang W C, Yao T D, Gao Y, Yang X X and Kattel D B 2011 A first-order method to identify potentially dangerous glacial lakes in a region of the southeastern Tibetan Plateau; *Mountain Res. Develop.* **31**(2) 122–130.
- Wang S J, Qin D H and Ren J W 2012a Progress and prospect on risk assessment of glacial lake outburst hazards; *Adv. Water Sci.* **23**(5) 735–742 (in Chinese).
- Wang X, Liu S, Ding Y, Guo W, Jiang Z, Lin J and Han Y 2012b An approach for estimating the breach probabilities of moraine-dammed lakes in the Chinese Himalaya using remote-sensing data; *Nat. Hazards Earth Syst. Sci.* **12** 3109–3122.
- Wang W C, Xiang Y, Gao Y, Lu A X and Yao T D 2014 Rapid expansion of glacial lakes caused by climate and glacier retreat in the central Himalaya; *Hydrol. Process.*, doi: [10.1002/hyp.10199](https://doi.org/10.1002/hyp.10199).
- Xiang Y, Gao Y and Yao T D 2014 Glacier change in the Poiqur River basin inferred from Landsat data from 1975 to 2010; *Quater. Int.*, doi: [10.1016/j.quaint.2014.03.017](https://doi.org/10.1016/j.quaint.2014.03.017).
- Yafazova R K 2007 Priroda selei Zailiiskogo Alatau. Problemy adaptatsii [Nature of Debris Flows in the Zailiysky Alatau Mountains. Problems of adaptation]; Almaty (in Russian).
- Yao T, Yao T D, Li Z G, Yang W, Guo X J, Zhu L P, Kang S C, Wu Y H and Yu W S 2010 Glacial distribution and mass balance in the Yarlung Zangbo River and its influence on lakes; *Chinese Sci. Bull.* **55**(20) 2072–2078.

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