Nat. Hazards Earth Syst. Sci. Discuss., 1, 15–37, 2013
www.nat-hazards-earth-syst-sci-discuss.net/1/15/2013/
doi:10.5194/nhessd-1-15-2013

Natural Hazards and Earth System Sciences
Open Access
Discussions

Potential flood volume of Himalayan glacial lakes

K. Fujita[1], A. Sakai[1], S. Takenaka[2], T. Nuimura[1], A. B. Surazakov[3], T. Sawagaki[4], and T. Yamanokuchi[5]

[1]Graduate School of Environmental Studies, Nagoya University, Nagoya, Japan
[2]Earth System Science, Co. Ltd., Tokyo, Japan
[3]College of Science, University of Idaho, Moscow, Idaho, USA
[4]Graduate School of Environmental Science, Hokkaido University, Sapporo, Japan
[5]Remote Sensing Technology Centre of Japan, Tsukuba, Japan

Received: 2 January 2013 – Accepted: 15 January 2013 – Published: 29 January 2013

Correspondence to: K. Fujita (cozy@nagoya-u.jp)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Glacial lakes are potentially dangerous sources of glacial lake outburst floods (GLOFs), and represent a serious natural hazard in Himalayan countries. Despite the development of various indices aimed at determining the risk of such flooding, an objective evaluation of the thousands of Himalayan glacial lakes has yet to be completed. In this study we propose a single index, based on the depression angle from the lakeshore, which allows the lakes to be assessed using remotely sensed digital elevation models (DEMs). We test our approach on five lakes in Nepal, Bhutan, and Tibet using images taken by the declassified Hexagon KH-9 satellite before these lakes flooded. All five lakes had a steep lakefront area (SLA), on which a depression angle was steeper than our proposed threshold of 10° before the GLOF event, but the SLA was no longer evident after the events. We further calculated the potential flood volume (PFV); i.e. the maximum volume of floodwater that could be released if the lake surface was lowered sufficiently to eradicate the SLA. This approach guarantees repeatability because it requires no particular expertise to carry out. We calculated PFVs for more than 2000 Himalayan glacial lakes using the ASTER data. The distribution follows a power-law function, and we identified 49 lakes with PFVs of over 10 million m^3 that require further detailed field investigations.

1 Introduction

Glacial lake outburst floods (GLOFs) represent a serious natural hazard in Himalayan countries (e.g. Vuichard and Zimmermann, 1987; Yamada, 1998; Dwivedi et al., 2000; Richardson and Reynolds, 2000; Mool et al., 2001a, b). Consequently, assessing the likely risk of a GLOF from individual glacial lakes is important when allocating limited human and financial resources to potential countermeasures. Although detailed in situ surveys have been able to quantify the potential risk of flooding from individual glacial lakes (Reynolds, 1999; Iwata et al., 2002; Fujita et al., 2008), it is impractical to perform such ground-based investigations on the thousands of Himalayan glacial lakes. A remote sensing approach offers a possible solution to this problem in the Himalayas, where ground-based measurements are hampered by the high altitude and remoteness (Bolch et al., 2008; Wang et al., 2008; Wang et al., 2011). In particular, 44 glacial lakes in Bhutan and Nepal have been identified as potentially dangerous glacial lakes (Mool et al., 2001a, b). Although many indices have been proposed by previous studies (Clague and Evans, 2000; Richardson and Reynolds, 2000; McKillop and Clague, 2007a, b; Bolch et al., 2008; Wang et al., 2008; X. Wang et al., 2012), uncertainties remain with respect to the choice of the most effective criteria with which to objectively evaluate GLOF risk.

Most previous studies have focused on the expansion rates of glacial lakes, and the steep terrain surrounding the lakes from which an ice/rock mass could fall into the lake (Richardson and Reynolds, 2000; Bolch et al., 2008; Wang et al., 2008), while only a few studies have examined the stability of the damming moraine as this requires the collection of in situ data (Clague and Evans, 2000; Hambrey et al., 2008; Fujita et al., 2009; Ohashi et al. 2012). As glacial lakes are situated in remote mountainous areas, the actual trigger for GLOF events has rarely been witnessed (Dwivedi et al., 2000). On the other hand, V-shaped trench cutting the damming moraine and debris fan in front of the lake provided evidences of dam breaches caused by GLOF (Komori et al., 2012). Consequently, in this study we assume that failure of the damming moraine is essential to release an effective amount of lake water, regardless of the trigger mechanism. Using recent evidence of a link between the topography of lakes and the surrounding areas (Clague and Evans, 2000; McKillop and Clague, 2007a, b; Fujita et al., 2008, 2009; Komori et al., 2012), we propose a new, single index to objectively quantify the potential risk from glacial lakes that is based on a simple remote sensing approach.

2 Methods

To evaluate the likely risk of a GLOF occurring, we developed an index based on the depression angle between the level of the lake surface and the surrounding terrain (Fig. 1) using remotely sensed DEMs. Although the depression angle is simply an alternative measurement of the width-to-height ratio of the damming moraine (Clague and Evans, 2000; Huggel et al., 2002; McKillop and Clague, 2007a, b), this angle can be easily calculated from DEMs, whereas it is often difficult to identify moraine boundaries from satellite imagery and thus the width-to-height ratio itself may have a large uncertainty associated with it.

We examined the terrain within 1 km of the targeted lakes and calculated the elevation angle from a given point towards the lake surface (i.e. the depression angle from the lake); the steepest angle measured (i.e. to the nearest section of lakeshore) was taken as the value for that point. As absolute consistency is required between the visible image and the digital elevation model (DEM), we used a Level 3A01 product from the ASTER orthorectified images, including a relative DEM (spatial resolution of 15 m) for the present-day analysis. This is a semi-standard orthorectified image generated from the Level-1A data by the ASTER Ground Data System (ASTER GDS) at the Earth Remote Sensing Data Analysis Centre (ERSDAC) in Japan. The relative DEM was produced with data from two telescopes, one a nadir-looking visible/near-infrared (VNIR) (band 3N) and the other a backward-looking VNIR (band 3B) without ground control point correction for individual scenes (Fujisada et al., 2005).

Having determined the threshold angle (10° as described later), we can define the steep lakefront area (SLA) in front of the glacial lake (Fig. 1). As the glacial lakes have no SLA after the GLOF events, we excluded lakes without an SLA from the following analysis. We assumed a potential lowering height (Hp) that would lead to the removal of the SLA if the lake surface was lowered without any change in the shoreline following outburst (Fig. 1). Some small glacial lakes have a very deep Hp if they are situated above a very large and steep slope. However, it is implausible that such small lakes (ca. 0.01 km^2, for instance) are deeper than 100 m, which is equivalent to the maximum depth of some typical Himalayan glacial lakes which may be up to 1 km^2 in area (Yamada, 1998; Fujita et al., 2009). We therefore constrained the depth of glacial lakes based on an empirical area-depth relationship (Fig. 2):

$$\mathrm{Dm} = 55A^{0.25} \tag{1}$$

where A and Dm are the lake area (km^2) and mean depth of the lake (m), respectively. This is the maximum approximation as shown in Fig. 2. Here, we use the mean depth, rather than the maximum depth, to estimate flood volume because the GLOF events did not result in the complete drainage of the lake. Finally, we obtained the potential flood volume (PFV) from:

$$\mathrm{PFV} = \min[\mathrm{Hp};\mathrm{Dm}]A. \tag{2}$$

We used whichever of the potential lowering height (Hp) or the mean depth (Dm) had the smaller value for the lowering height in the event of outburst, and assumed a cylindrical bathymetry (i.e. no change in lakeshore following a lowering in lake level) to calculate the maximum flood volume, because lake bathymetry cannot be obtained using remote sensing techniques.

It would be realistic to simply assume, for instance, that a large lake in flat terrain has no outburst risk at all, while a typical Himalayan glacial lake, with its steep and narrow dam, must have a very high outburst potential (Costa and Schuster, 1988). We therefore expect that the probability of a GLOF event is related to some threshold value of the depression angle. But how steep is this threshold? To determine the threshold angle, we used declassified Hexagon KH-9 satellite imagery obtained between 1973 and 1980 of five glacial lakes in Nepal, Bhutan, and Tibet, for which pre-GLOF images were available (Table 1). We generated Hexagon KH-9 DEMs with a resolution of 10 m from stereo pair images. First, image distortion, which was introduced by the development and double duplication of the film, and almost three decades of storage, was corrected by the method proposed by Surazakov and Aizen (2010). Second, a detailed terrain editing procedure was performed on the triangulated irregular network using the Leica Terrain Format software to further correct and reduce errors related to the irregular microtopography, high relief, and shadows on the images (Lamsal et al., 2011; Sawagaki et al., 2012). Finally, we performed the same procedure on the ASTER data to obtain the depression angle around the five glacial lakes before the GLOF events.

We identified 2276 glacial lakes across the Himalayas on 146 scenes of ASTER data by referring to the normalized differentiated water index (Huggel et al., 2002; Bolch et al., 2008; Fujita et al., 2009). We confined our targets to moraine dammed lakes situated within the latest moraine formed during the Little Ice Age, and excluded supraglacial ponds, and lakes dammed by glaciers (Fig. 3), because their drainage-induced flood mechanism may be different to floods caused by dam collapse (Komori et al., 2012).

3 Results

We compared pre- and post-GLOF images from five lakes in Nepal, Bhutan, and Tibet (Table 1; Fig. 4). Pre-GLOF images obtained from the Hexagon KH-9 satellite show that all five lakes had a SLA to their damming moraine, but no SLA was observed in front of the lakes after the flood if a threshold of 10° is assumed for the depression angle. This suggests that the collapse of the damming moraine may have ceased when the slope of the flood channel became less than 10° when it then, once again, acted as a robust dam. This also suggests that a glacial lake with no SLA would be unlikely to suffer a GLOF. A previous dam breach simulation also suggested that a gently sloping moraine (<10°) could not initiate a breach, even under a large water inflow (Koike and Takenaka, 2012).

We applied the criteria to 2276 glacial lakes across the Himalayas whose area is larger than 0.005 km^2 (Table 2; Fig. 5). The PFVs and actual flood volumes estimated by alternative methods (hydrograph or in situ survey) for the three GLOF lakes (Dig, Sabai and Lugge) were fairly similar (Table 1). We found that 794 lakes did not have an SLA, and consequently had a PFV of zero. Within this group, 23 lakes have been categorized as potentially dangerous glacial lakes (PDGLs), although 44 lakes were originally identified in Bhutan and Nepal (Table S1, Mool et al., 2001a, b). Consequently, these 23 lakes can be excluded from the group of PDGLs based on our criteria. The remaining 21 lakes still show some degree of PFV (10 lakes in Nepal and 11 in Bhutan; Table S1). The number of lakes decreases with the PFV according to a power-law distribution (Fig. 6a). We list 49 lakes having a significant PFV (greater than 10 million m^3), which is a comparable volume to that of recorded major GLOFs (Table S2). Figure S1 shows 18 lakes having PFV greater than 20 million m^3. Major glacial lakes with a large PFV value appear to be located around the eastern Nepal to Bhutan Himalayas (Fig. 5), where glacial lakes show rather rapid expansion rates (Gardelle et al., 2011). This implies that the PFV will increase over time associated with expansion of the lake area.

4 Error evaluation

Of the 2276 Himalayan glacial lakes, 931 were examined several times using data taken on different dates. We selected lakes with the most accurate surface elevation data (smaller standard deviation of lake elevation). We found 103 lakes having a standard deviation greater than 13 m, while the accuracy of the elevation data in the DEMs derived from ASTER satellite images in the Bhutan and Nepal Himalayas was 12.9 ± 1.9 m, and depends on image quality (cloud and/or snow cover) (Fujita et al., 2008; Nuimura et al., 2012). The measured surface elevation of 94.4 % of the glacial lakes had standard errors of less than 1 m (Fig. 6b).

We examined how the potential flood volume of Himalayan glacial lakes responds to the threshold angle (Fig. 6a; Table S3). Steep lakefront area (SLA) and associated potential flood volume (PFV) irregularly appeared (or disappeared) when the threshold angle has decreased (or increased) because the SLA depended on relative location among lakeshore and surrounding moraine and the PFV depended on lowering lake level (related to the SLA) and lake area. In any threshold angles, the distributions follow a power-law function (Fig. 6a).

5 Discussion

The calculated PFV represents a maximum projection because we assume a cylindrical bathymetry, and this implies no change in the shoreline following lowering of the lake surface by the flooding, while the bathymetry of real glacial lakes gradually deepens from the downstream to the upstream side (Yamada, 1998; Fujita et al., 2009). Considering such a shallow bathymetry, the lowering of the lake surface by flooding would result in the retreat of the lakeshore upstream causing the SLA to be removed more quickly than would be the case for the assumed cylindrical bathymetry. On the other hand, downstream expansion of a glacial lake will result in the formation of a new SLA in front of the lake. This implies that glacial lakes with a PFV of zero may suddenly develop a very high PFV if the lake has a large surface area. In fact, Nagma Pokhari in the Nepal Himalayas showed no SLA in 1973, but downstream expansion has led to the development of an SLA and a significant PFV (32.8 million m^3; Table 1) in only two years (Fig. S2). In contrast, a case study of the Imja Glacial Lake, which is the most investigated Himalayan glacial lake (e.g. Yamada, 1998; Bajracharya et al., 2007; Bolch et al., 2008; Fujita et al., 2009; Hambrey et al., 2008; Lamsal et al., 2011), showed that the downstream shoreline has been stable since the 1990s (Fujita et al., 2009). Our analysis shows a PFV of zero for the Imja Glacial Lake, and it seems to be in a much safer state than other lakes with large PFVs. Nevertheless, slow but continuous lowering of the moraine dam (Fujita et al., 2009) may possibly result in future changes to the lakeshore downstream. Therefore, continuous monitoring of such large-scale lakes is required, even if they have a zero PFV at present.

Figure 7a and b show that the PFV of many Himalayan glacial lakes is constrained by the relationship between lake area and mean depth (Fig. 2). This suggests that glacial lakes with SLAs tend to have a larger potential lowering height (Hp) than their mean depth (Dm). It is reasonable to constrain the PFV using mean depth because those lakes that experienced a GLOF were not fully drained (Fig. 1). The relationship between the SLA and the PFV (Fig. 3c), and between the average depression angle of the SLA and the PFV (not shown), suggest that neither the extent of the SLA, nor its steepness, affects the PFV. The five GLOF lakes studied here also suggest that the extent of the SLA would not correlate with the probability of their outburst due to their very small SLAs (Table 1; Fig. 4). We also calculated a minimum distance (MD) between the lakeshore and SLA (Fig. 1). Our five GLOF lake sites showed an MD of less than 200 m. The MD is another measure of the width of the moraine dam, and a shorter MD implies a narrower dam and so may suggest a higher probability of outburst (Fig. 3d), although it is difficult to estimate a threshold distance.

6 Conclusions

Despite the existence of lakes with large PFVs, the practical requirement to implement countermeasures will be low if the downstream river is uninhabited and/or undeveloped. In contrast, even those glacial lakes with PFVs of less than 10 million m^3 may have to be investigated in detail if they are situated at the head of a densely populated river valley. Despite its rather small flood volume of 5.0 million m^3 (PFV estimated to be 7.1 million m^3; Table 1), the 1985 flood from Dig Tsho in Nepal seriously damaged infrastructure, including a newly built hydropower plant, along the Bhote Kosi and Dudh Kosi rivers, which is one of the most visited trekking routes in the world (Vuichard and Zimmermann, 1987). Further flood simulation work will aid the ongoing prioritization of those glacial lakes likely to require flood prevention measures (Bajracharya et al., 2007; Koike and Takenaka, 2012; W. Wang et al., 2012), and a high-quality DEM is essential for such simulations (W. Wang et al., 2012).

Our analysis does not clarify the stability of the damming moraine. For instance, a bedrock dam should be less susceptible to breaching, even if the lake is situated at the top of a steep slope. Some Andean glacial lakes have bedrock dams, and here failure of the dam is less likely to be a cause of flooding than the risk of mass movement from the surrounding walls (Carey et al., 2012). However, these aspects cannot be evaluated using current remote sensing technology. In situ investigation is the only way to definitively determine the lithology and structure of a moraine dam (Hambrey et al., 2008; Ohashi et al., 2012) as well as the bathymetry of the glacial lake (Yamada, 1998; Fujita et al., 2009). Nevertheless, it is impractical to conduct ground-based surveys of thousands of Himalayan glacial lakes. The concepts of SLA and PFV proposed in this study are practical indices that can be easily calculated, without any particular expertise, if remotely sensed imagery and DEMs are available. The PFV list prioritizes those Himalayan glacial lakes that require further detailed investigation. In addition to in situ surveys to confirm the present status of lakes with large PFVs, it is also necessary to continue monitoring the other Himalayan glacial lakes because changes to lakeshores will not only alter existing PFVs, but may also lead to the development of new SLAs and hence PFVs.

Supplementary material related to this article is available online at: http://www.nat-hazards-earth-syst-sci-discuss.net/1/15/2013/nhessd-1-15-2013-supplement.zip.

Acknowledgements. This study was conducted under the Science and Technology Research Partnership for Sustainable Development (SATREPS) supported by the Japan Science and Technology Agency (JST) and the Japan International Cooperation Agency (JICA).

References

Bajracharya, B., Shrestha, A. B., and Rajbhandari, L.: Glacial lake outburst floods in the Sagarmatha region: hazard assessment using GIS and hydrodynamic modeling, Mt. Res. Dev., 27, 336–344, doi:10.1659/mrd.0783, 2007.

Benn, D. I., Wiseman, S., and Warren, C. R.: Rapid growth of a supraglacial lake, Ngozumpa Glacier, Khumbu Himal, Nepal, Int. Assoc. Hydrol. Sci., 264, 177–185, 2000.

Bolch, T., Buchroithner, M. F., Peters, J., Baessler, M., and Bajracharya, S.: 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, doi:10.5194/nhess-8-1329-2008, 2008.

Carey, M., Huggel, C., Bury, J., Portocarrero, C., and Haeberli, W.: An integrated socio-environmental framework for glacier hazard management and climate change adaptation: lessons from Lake 513, Cordillera Blanca, Peru, Climatic Change, 12, 733–767, doi:10.1007/s10584-011-0249-8, 2012.

Clague, J. J. and Evans, S. G.: Formation and failure of natural dams in the Canadian Cordillera, Bull. Geol. Surv. Can., 464, p. 35, 1994.

Clague, J. J. and Evans, S. G.: A review of catastrophic drainage of moraine-dammed lakes in British Columbia, Quaternary Sci. Rev., 19, 1763–1783, doi:10.1016/S0277-3791(00)00090-1, 2000.

Costa, J. E. and Schuster, R. L.: The formation and failure of natural dams, Geol. Soc. AM. Bull., 100, 1054–1068, doi:10.1130/0016-7606(1988)100<1054:TFAFON>2.3.CO;2, 1988.

Dwivedi, S. R., Acharya, M. D., and Simard, R.: The Tam Pokhari Glacier Lake outburst flood of 3 September 1998, J. Nepal Geol. Soc., 22, 539–546, 2000.

Fujisada, H., Bailey, G. B., Kelly, G. G., Hara, S., and Abrams, M. J.: ASTER DEM performance, IEEE T. Geosci. Remote Sens., 43, 2702–2714, doi:10.1109/TGRS.2005.847924, 2005.

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

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

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

Hambrey, M. J., Quincey, D. J., Glasser, N. F., Reynolds, J. M., Richardson, S. J., and Clemmens, S.: Sedimentological, geomorphological and dynamic context of debris-mantled glaciers, Mount Everest (Sagarmatha) region, Nepal, Quaternary Sci. Rev., 27, 2361–2389, doi:10.1016/j.quascirev.2008.08.010, 2008.

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

International Centre for Integrated Mountain Development: Glacial lakes and glacial lake outburst floods in Nepal, ICIMOD, Kathmandu, Nepal, 99 pp., 2011.

Iwata, S., Ageta, Y., Naito, N., Sakai, A., Narama, C., and Karma: Glacial lakes and their outburst flood assessment in the Bhutan Himalaya, Global Environ. Res., 6, 3–17, 2002.

Koike, T. and Takenaka, S.: Scenario analysis on risks of glacial lake outburst floods on the Mangde Chhu River, Bhutan, Global Environ. Res., 16, 41–49, 2012.

Komori, J., Koike, T., Yamanokuchi, T., and Tshering, P.: Glacial lake outburst events in the Bhutan Himalayas, Global Environ. Res., 16, 59–70, 2012.

Lamsal, D., Sawagaki, T., and Watanabe, T.: Digital terrain modelling using Corona and ALOS PRISM data to investigate the distal part of Imja Glacier, Khumbu Himal, Nepal, J. Mt. Sci., 8, 390–402, doi:10.1007/s11629-011-2064-0, 2011.

Liu, C. and Sharma, C. K.: Report on first expedition to glaciers and glacier lakes in the Pumqu (Arun) and Poiqu (Bhote-SunKosi) River Basin, Xizang (Tibet), China, Science Press, Beijing, China, 192 pp., 1988.

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

McKillop, R. J. and Clague, J. J.: Statistical, remote sensing-based approach for estimating the probability of catastrophic drainage from moraine-dammed lakes in southwestern British Columbia, Global Planet. Chang., 56, 153–171, doi:10.1016/j.gloplacha.2006.07.004, 2007b.

Mool, P. K., Bajracharya, S. R., and Joshi, S. P.: Inventory of glaciers, glacial lakes and glacial lake outburst floods, Nepal, ICIMOD, Kathmandu, Nepal, 363 pp., 2001a.

Mool, P. K., Wangda, D., Bajracharya, S. R., Kunzang, K., Gurung, D. R., and Joshi, S. P.: Inventory of glaciers, glacial lakes and glacial lake outburst floods, Bhutan, ICIMOD, Kathmandu, Nepal, 227 pp., 2001b.

Nuimura, T., Fujita, K., Yamaguchi, S., and Sharma, R. R.: Elevation changes of glaciers revealed by multitemporal digital elevation models calibrated by GPS survey in the Khumbu region, Nepal Himalaya, 1992–2008, J. Glaciol., 58, 648–656, doi:10.3189/2012JoG11J061, 2012.

Ohashi, K., Koike, T., Takenaka, S., and Umemura, J.: Study on applicability of electric sounding for interpretation of the internal structure of glacial moraines, Global Environ. Res., 16, 51–58, 2012.

Reynolds, J. M.: Glacial hazard assessment at Tsho Rolpa, Rolwaling, central Nepal, Q. J. Eng. Geol. Hydroge., 32, 209–214, 1999.

Richardson, S. D. and Reynolds, J. M.: An overview of glacial hazards in the Himalayas, Quaternary Int., 65/66, 31–47, doi:10.1016/S1040-6182(99)00035-X, 2000.

Sakai, A.: Glacial lakes in the Himalayas: a review on formation and expansion processes, Global Environ. Res., 16, 23–30, 2012.

Sawagaki, T., Lamsal, D., Byers, A. C., and Watanabe, T.: Changes in surface morphology and glacial lake development of Chamlang South Glacier in the eastern Nepal Himalaya since 1964, Global Environ. Res., 16, 83–94, 2012.

Surazakov, A. B. and Aizen, V. B.: Positional accuracy evaluation of declassified Hexagon KH-9 mapping camera imagery, Photogramm. Eng. Rem. S., 76, 603–608, 2010.

Vuichard, D. and Zimmerman, M.: The 1985 catastrophic drainage of a moraine-dammed lake, Khumbu Himal, Nepal: cause and consequences, Mt. Res. Dev., 7, 91–110, doi:10.2307/3673305, 1987.

Wang, W., Yao, T., Gao, Y., Yang, X., and Kattel, D. B.: A first-order method to identify potentially dangerous glacial lakes in a region of the southeastern Tibetan Plateau, Mt. Res. Dev., 31, 122–130, 2011.

Wang, W., Yang, X., and Yao, T.: Evaluation of ASTER GDEM and SRTM and their suitability in hydraulic modelling of a glacial lake outburst flood in southeast Tibet, Hydrol. Process., 26, 213–225, doi:10.1002/hyp.8127, 2012.

Wang, X., Liu, S., Guo, W., and Xu, J.: Assessment and simulation of glacier lake outburst floods for Longbasaba and Pida lakes, China, Mt. Res. Dev., 28, 310–317, doi:10.1659/mrd.0894, 2008.

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

Yamada, T.: Glacier lake and its outburst flood in the Nepal Himalaya, Monograph No. 1, Data Center for Glacier Research, Japanese Society of Snow and Ice, Tokyo, 96 pp., 1998.

Yamada, T., Naito, N., Kohshima, S., Fushimi, H., Nakazawa, F., Segawa, T., Uetake, J., Suzuki, R., Sato, N., Karma, Chhetri, I. K., Gyenden, L., Yabuki, H., and Chikita, K.: Outline of 2002 – research activities on glaciers and glacier lakes in Lunana region, Bhutan Himalayas, Bull. Glaciol. Res., 21, 79–90, 2004.

Table 1. Characteristics of the five GLOF lakes studied.

Lake	Area (km^2)	LON (°)	LAT (°)	Z (m a.s.l.)	SLA (km^2)	MD (m)	Hp (m)	Dm (m)	PFV (million m^3)	FV (million m^3)	Hexagon acquisition date	ASTER acquisition date	Date of outburst
Nagma	0.66	87.867	27.870	4858	0.244	28	60	50	32.8	N/A	20 Dec 1975	19 Nov 2007	23 Jun 1980
Dig	0.34	86.584	27.875	4336	0.050	255	21	42	7.1	5.0	21 Nov 1973	23 Jan 2006	4 Aug 1985
Lugge	1.14	90.296	28.094	4544	0.029	14	13	57	14.9	17.2	24 Nov 1974	1 Jan 2008	7 Oct 1994
Sabai/Tam	0.38	86.845	27.743	5227	0.357	193	52	43	16.3	17.7	14 Dec 1973	23 Jan 2006	3 Sep 1998
Unnamed	0.46	89.745	28.211	4812	0.066	168	16	45	7.2	N/A	5 Nov 1974	9 Dec 2002	unknown

Abbreviations denote longitude (LON), latitude (LAT), altitude (Z), steep lookdown area (SLA), minimum distance between lakeshore and SLA (MD), potential lowering height (Hp), mean depth estimated from lake area (Dm), potential flood volume (PFV), and flood volume (FV). Flood volumes are based on previous studies (Vuichard and Zimmermann, 1987; Dwivedi et al., 2000; Fujita et al., 2008). Lake area of Lugge Tsho is based on a SPOT image taken one year before the GLOF event (Fujita et al., 2008).

Title Page
Abstract
Introduction
Conclusions
References
Tables
Figures
◂
▸
Back
Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

Table 2. Potential flood volume (PFV) of Himalayan glacial lakes

PFV (million m^3)	Number of lakes
0	794
<1	1002
1–5	370
5–10	61
10–20	31
>20	18
Total	2276

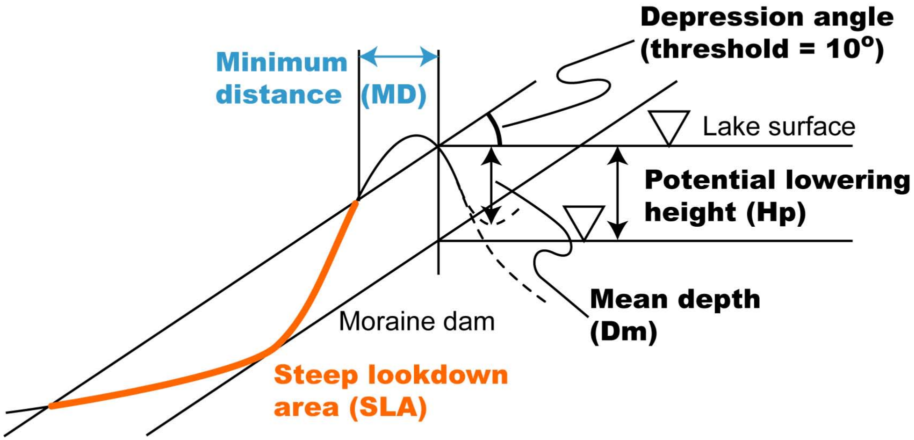

Fig. 1. The concept of the steep lookdown area (SLA), potential lowering height (Hp), mean depth (Dm), and minimum distance (MD) for a glacial lake. The threshold angle (10°) used to define the SLA was obtained by evaluating pre-GLOF topography in Hexagon KH-9 images (Fig. 4). The value of either Hp or Dm (whichever was the lowest) was used together with the lake surface area to calculate the potential flood volume (PFV).

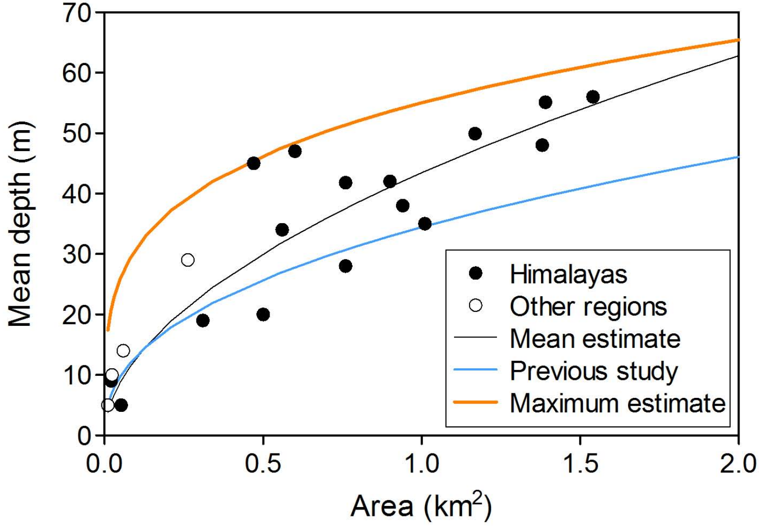

Fig. 2. Observational relationship between lake area and mean depth of Himalayan glacial lakes (solid dots) (Vuichard and Zimmermann, 1987; Liu and Sharma, 1988; Yamada, 1998; Benn et al., 2000; Dwivedi et al., 2000; Yamada et al., 2004; Fujita et al., 2009; ICIMOD, 2011; Sakai, 2012). Open dots are moraine-dammed lakes in other regions of the world (Clague and Evans, 2000; Huggel et al., 2002). Black, blue, and orange lines show an approximate curvilinear fit for the observational data, and for other glacial lakes worldwide (Huggel et al., 2002), and the maximum approximate curve used to constrain lake depth in this study, respectively.

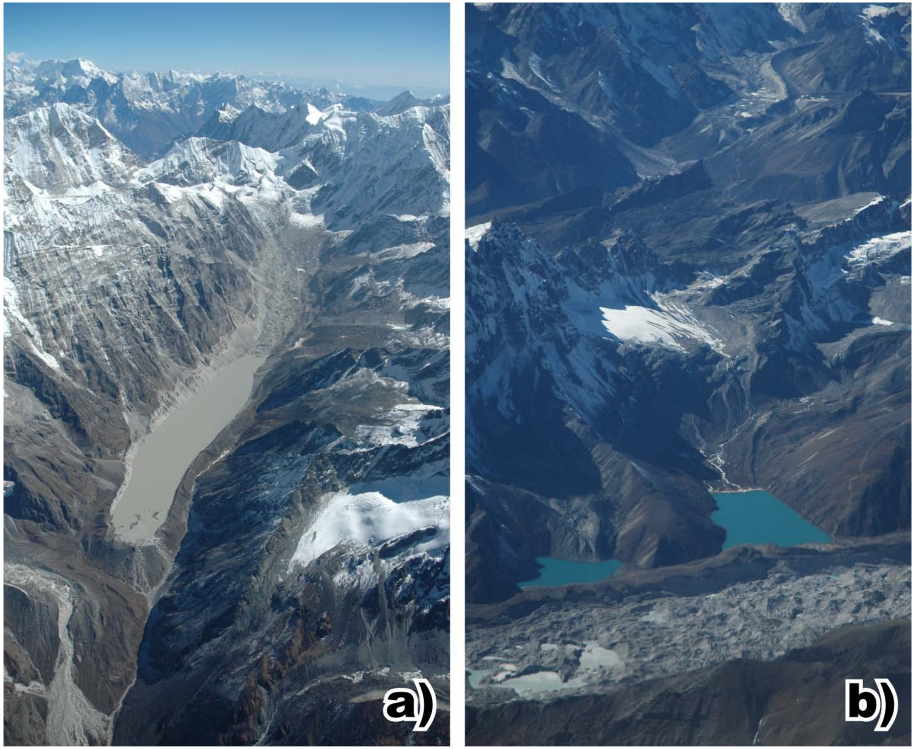

Fig. 3. Moraine-dammed lake examined in this study (**a** Tsho Rolpa having the greatest potential flood volume) and glacier-dammed lake excluded from the analysis (**b** Gokyo Tsho). Both lakes are in Nepal. Photos taken in November 2007.

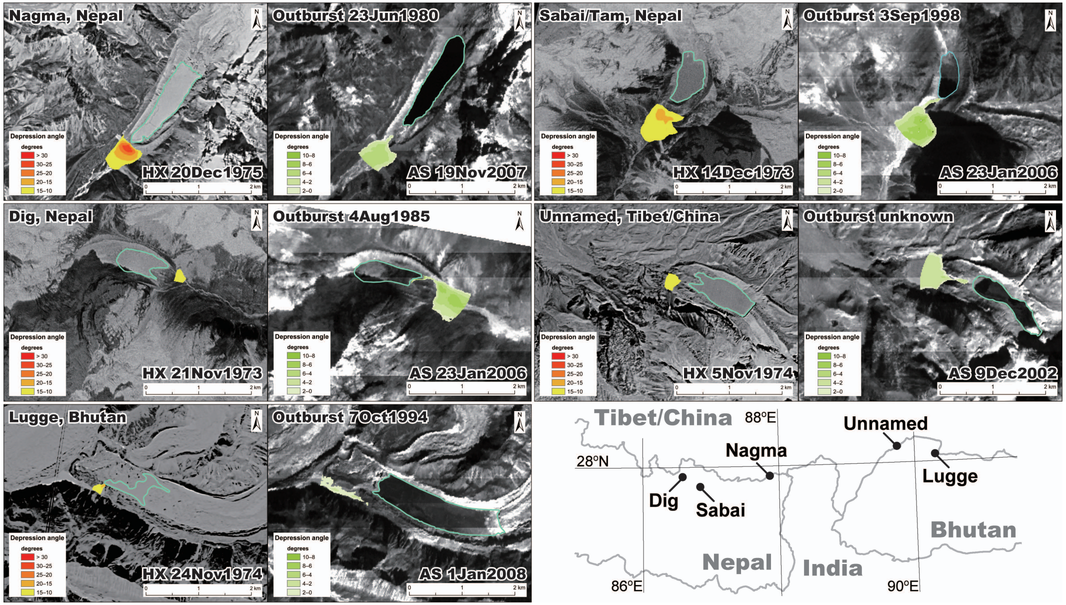

Fig. 4. Pre- (HX) and post-GLOF (AS) images of the five lakes showing changes in depression angle. Details in Table 1. Acquisition dates area indicated after HX (Hexagon) and AS (ASTER).

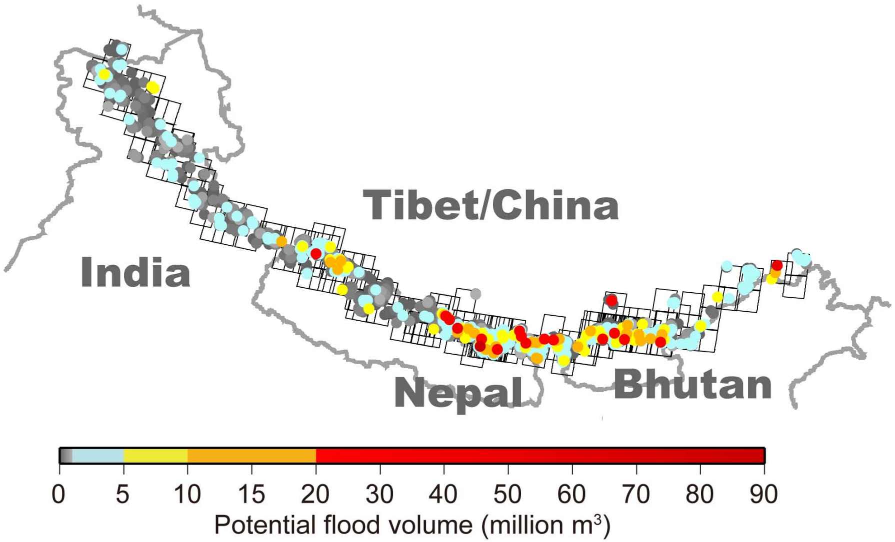

Fig. 5. Potential flood volume (PFV) of 2276 Himalayan glacial lakes. Smaller lakes are obscured by larger ones. Squares denote coverage of ASTER images used in the analysis.

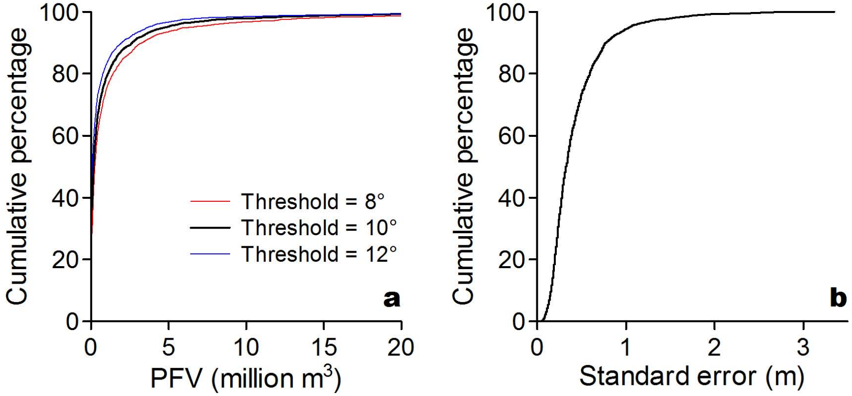

Fig. 6. Cumulative frequency distributions for the 2276 Himalayan glacial lakes against potential flood volume (PFV) **(a)** and standard error of lake surface elevation **(b)**. PFVs in the different threshold depression angles are depicted. Lakes having PFV greater than 20 million m^3 are not depicted.

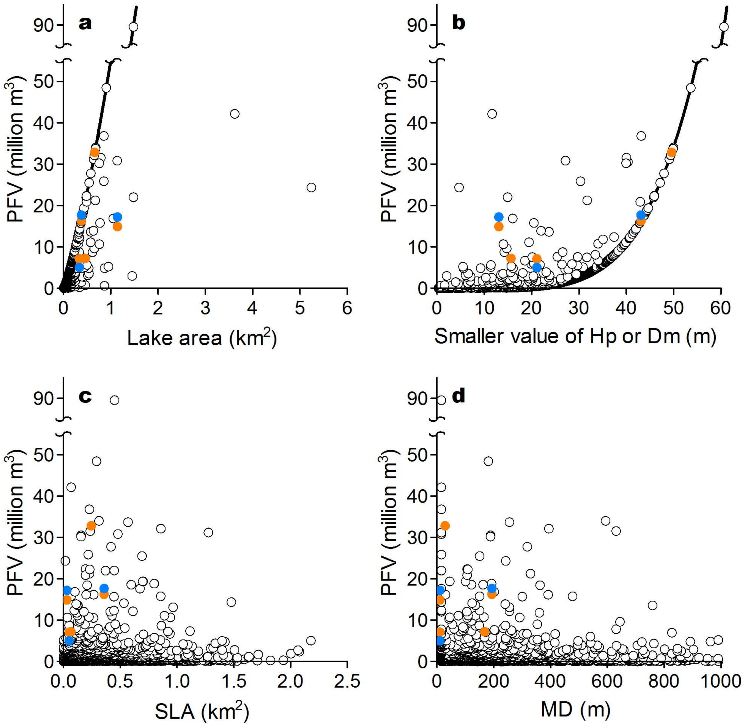

Fig. 7. Relationships of PFV with lake area **(a)**, Hp or Dm (whichever is smaller) **(b)**, SLA **(c)**, and MD **(d)** for 2276 Himalayan glacial lakes (open circles). Coloured circles indicate estimates based on the method developed in this study (orange) and by other approaches (blue) for the five GLOF lakes (See Fig. 4 and Table 1). Thick lines in **(a)** and **(b)** indicate PFV values constrained by Eq. (1), which is based on the maximum approximation of the lake's mean depth (Fig. 2).