Outline of Research Project on Glacial Lake Outburst Floods in the Bhutan Himalayas

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Abstract

Glacial Lake Outburst Floods (GLOFs) are a major hazard of concern to mountain communities in the Himalayas. In 2009 we started a three-year research project, in which we have conducted evaluation of GLOF risk using satellite data, *in-situ* surveys, and breach and flood simulations, and have produced a hazard map of possible floods. We have primarily focused on the Mangde-Chhu basin, for which the GLOF hazard level has been believed to be high but information regarding mitigation has been lacking. In this article, we describe the structure and strategy of the research project, and major results obtained to date.

Key words: bathymetry survey, Bhutan Himalaya, glacial lake outburst flood, hazard map, technology transfer

1. Introduction

A glacial lake outburst flood (GLOF) occurs when a body of water that is contained by a glacier or terminal moraine is released. In Himalayan countries such as Bhutan and Nepal, hazards from GLOFs are an urgent environmental and economical issue. Since the 1960s, a number of GLOFs have been recorded concurrent with shrinkage of glaciers and expansion of glacial lakes over the region. These observations have led to the notion that recent global warming may have resulted in an increasing amount of GLOF risk. However, many glacial lakes started to expand prior to the 1970s when the global average surface temperature began to increase most significantly. There is no clear indication that the rates at which glacial lakes are expanding have recently accelerated (Fujita *et al.*, 2009). Studies suggest a positive feedback between the enlargement of glacial lakes and the increasing amount of calving through melting and uplifting from buoyant effects (Röhl, 2008; Sakai *et al.*, 2009). This feedback process would provide a potential explanation for the expansion of glacial lakes within the context of natural variability. At present, a firm link has yet to be established between global warming and GLOF events. Our knowledge on GLOFs, including detailed geological and hydrological processes, is not sufficient to provide a comprehensive understanding of GLOF mechanisms (Yamada, 1998; Richardson & Reynolds, 2000).

Nonetheless, a great amount of effort has been put into assessing GLOF risk for potentially dangerous glacial lakes in this region. The International Centre for Integrated Mountain Development (ICIMOD) in Kathmandu, Nepal, reported that a total of 44 lakes in Nepal and Bhutan pose a danger of outbursts (Mool *et al.*, 2001a, 2001b). Although these efforts are well-spent, uncertainties remain as to what criteria we should choose for objectively evaluating GLOF risk. It is of our opinion that this question can be best answered through a comprehensive assessment of topography around potentially dangerous lakes with digital elevation data obtained from both satellites and field observations. Here the analysis period must be extended as far back as possible to gain a maximum amount of information on the lakes' history. The analysis area must also be extended to a larger area, assuring the validity of the study results.

An equally if not more urgent task is to find ways to prevent and adapt to the hazards of GLOFs. This can be accomplished by first constructing a hazard map. Here we need to consider the downstream topography of river channels and debris flows. Each lake or river basin must be evaluated on an individual basis. This calls for satellite data as it is the only possible means to acquire topographic and geographical information on a large number of lakes. The aim here must be towards gaining necessary information for objectively constructing hazard maps, optimizing warning systems, and performing drainage work in a cost-effective manner.

Punakha in Bhutan was inundated by a GLOF in 1994 which was triggered by an outburst from the Lugge Glacial Lake in the Lunana region, which is located 100 km upstream (Tashi, 1994). This event solidified coordination and cooperation in glacier and GLOF research between Bhutan and Japan. Responding in part to a request by the Bhutanese government in 1998, a team composed of researchers from Nagoya University, Tokyo Metropolitan University and the Bhutanese Department of Geology and Mines (DGM) made an initial assessment of GLOF risk using field observations (Ageta *et al*., 2000; Iwata *et al*., 2002; Yamada *et al*., 2004). This work sets a precedent for studying GLOFs from both academic and social points of view, leading to continuous cooperation between the DGM and Japanese researchers over the years.

This present project aims essentially to elevate the level of cooperation between the Bhutanese and Japanese in GLOF research to yet another level and was started in 2009 as one of the "Science and Technology Research Partnership for Sustainable Development (SATREPS)" programs supported by Japan Science and Technology Agency (JST) and Japan International Cooperation Agency (JICA). The plan is comprehensive, covering all three aspects of GLOF research, namely process studies, risk assessment, and prevention/adaptation. Therefore, one significant aspect of this research is that it provides a comprehensive package to Bhutanese society rather than just to its research community. In the same vein, the significance of this joint research lies in the fact that it works towards developing sustainable systems for GLOF adaptation and prevention through technology transfer. These two aspects guarantee high merits to Bhutanese society and meet standards for successful international research collaboration. In this paper, we give an outline of the GLOF project and achievements at this stage.

2. Structure and strategy of the research project

The ultimate goal of this research is to assess objectively GLOF risk in Bhutan and attempt to implement adaptation and prevention measures to curb both existing and future GLOF-related risks. Toward this goal the following steps are being taken. The project consists of three research groups: a process-group, satellite-group and assessment-group, and one counterpart in Bhutan (Department of Geology and Mines, DGM). The structure and strategy of the project is shown schematically in Fig. 1.

2.1 Reselection and risk assessment of dangerous glacial lakes

Over 40 glacial lakes in Nepal and Bhutan have been listed for their potential risk (Mool *et al*., 2001a, 2001b). Although many indices have been proposed to evaluate GLOF risk so far (Bolch *et al*., 2008; Wang *et al*., 2008), we think that the collapse of a damming moraine is essential to the release an effective amount of lake water, even after considering other triggers. On the basis of recently gained knowledge on a link between the topography of lakes and surrounding areas (Fujita *et al*., 2008, 2009), we propose a relative angle looking down from the lake surface as a single parameter for identifying the potential risk of a given glacial lake. The schematic figure in Fig. 2 explains the concept of the relative lookdown evaluation.

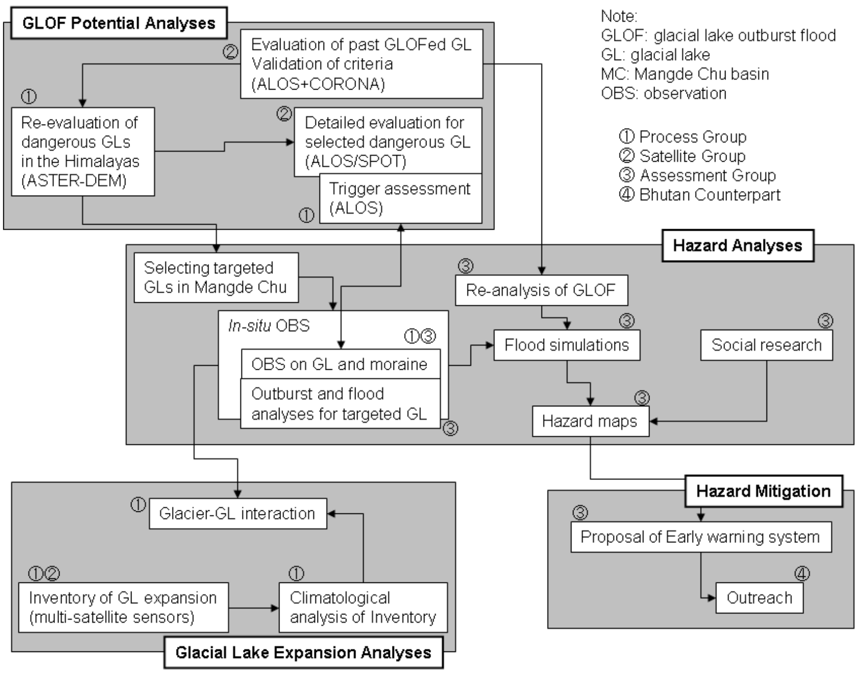

Fig. 1 Structure and strategy of the project for study on glacial lake outburst floods in the Bhutan Himalayas.

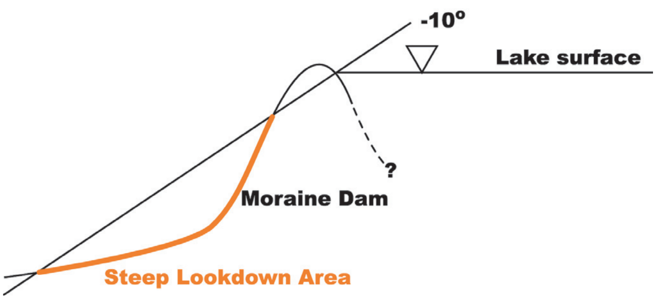

Fig. 2 Schematic figure of the concept of the relative lookdown evaluation for GLOF risk. A lookdown angle of −10° is a tentative value.

This idea is similar to the width-height ratio of the damming moraine, which has been proposed by Clague and Evans (2000). We simplify the dam-related parameters into one because it is difficult to determine the boundaries of damming moraines on remotely sensed images. Using this criterion, we chose pilot sites for our field survey. Our detailed analysis using ASTER data is now ready for publication.

2.2 Field surveys of high-risk glacial lakes

We conducted field surveys of glacial lakes in the Mangde-Chhu basin (Fig. 3), a previously unsurveyed river basin in the middle part of Bhutan, in which a pilot study pointed to GLOF potentials from seven glacial lakes (lakes with orange boundaries in Fig. 3, three potentially dangerous glacial lakes are also shown in the Lunana region) (Mool *et al*., 2001b). We set our focus on the residual strength of the damming moraine and other factors leading to outbreaks, as displayed schematically in Fig. 4. We utilized different technologies developed in different disciplines such as river engineering, geotechnical and geophysical exploration, using two-dimensional resistivity profiling and a micro-tremor array method to investigate the internal structure of moraines. The survey included sounding and drawing of bathymetric maps. To conduct field surveys in the Zanam region, one of the headwater regions in the Mangde-Chhu basin (Fig. 3), we spent the first year checking local accessibility and transportation and conducting preliminary field surveys of moraine structure, hydrology and glacier dynamics at pilot sites. In the second year, we conducted intensive surveys throughout the Mangde-Chhu basin. In the third year (the last year of the project), we made additional surveys not only in the Mangde-Chhu basin but also in the Lunana region to obtain data on changes in glaciers and glacial lakes since the previous surveys in 2004 (Fujita *et al*., 2008).

2.3 Hazard map of the Mangde-Chhu River

Numerical simulations to assess GLOF-associated risk for the Mangde-Chhu basin have been conducted (Koike & Takenaka, 2012). The breach model used in these simulations calculated bed erosion and horizontal widening of the outlet channel in the damming moraine by considering processes of sediment transportation and slope stability. Propagation of floods was calculated using a one-dimensional flood model, and then the highest water level was calculated using a two-dimensional flood model with high-resolution DEMs (digital elevation models). Rising water levels, valley topography and landslide risk on the river bank caused by flooding were taken into account. The simulation outputs were flood arrival times and the highest water level around targets requiring protection (habitats or infrastructures), from which a flood hazard map of the Mangde-Chhu basin was constructed.

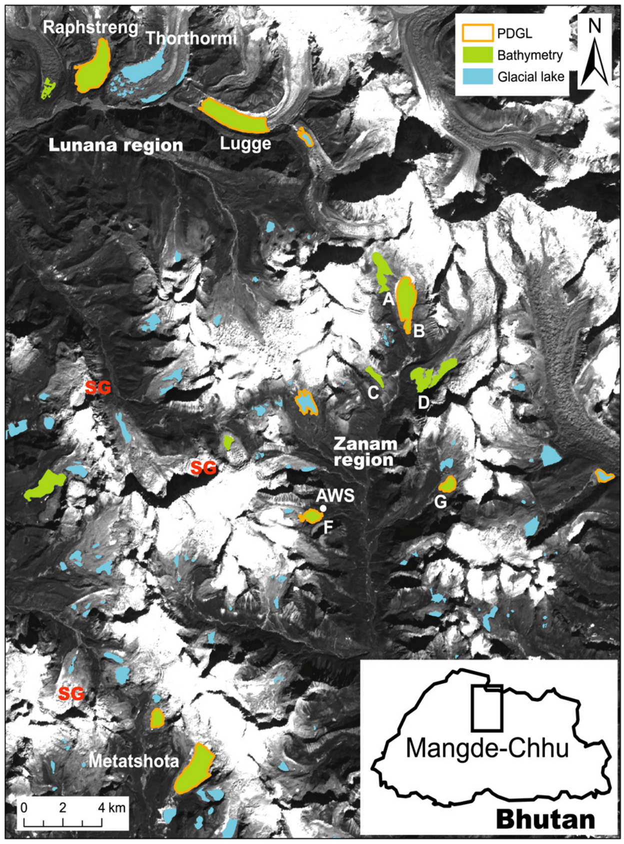

Fig. 3 Glacial lakes in the Zanam and Lunana regions, Bhutan Himalayas. PDGL and AWS denote potentially dangerous glacial lakes, which have been pointed out by the ICIMOD report (Mool *et al*., 2001b), and an automatic weather station installed near Lake Zanam F, respectively. Light green shading denotes glacial lakes for which we conducted bathymetry surveys through the project. SG denotes surveyed glaciers. The back image was taken by ASTER in 2008.

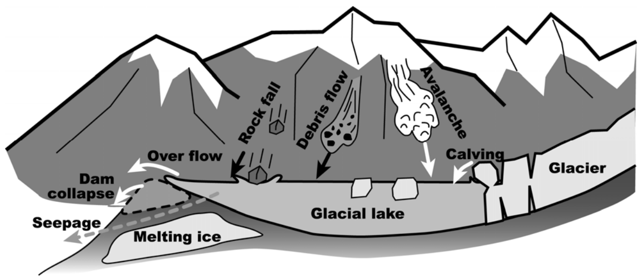

Fig. 4 Possible triggers of glacial lake outburst floods.

2.4 Understanding of glacial lake evolution

The above-described plans aim at directly assessing and adopting GLOF risk for existing glacial lakes. In the future it will also be essential to estimate possible impacts from global warming on the formation and expansion of glacial lakes. At present there is no established theory to explain the mechanism of glacial lake evolution, whereas Sakai *et al*. (2009) have proposed a positive feedback process with respect to glacial lake expansion by numerical simulation. Field surveys on the heat budget of glacial lakes, glacier dynamics, ice thickness of glaciers, meteorological conditions and other parameters are needed to elucidate the underlying physics of glacial lake formation and expansion. In the first year, an automatic weather station (AWS) was set beside Lake Zanam F (AWS in Fig. 3) to obtain meteorological data. These data provide important meteorological information from the high Himalayas where observational data have been scarce. Besides the dynamic approach, we also examined topographical features of glaciers in different states with respect to glacial lakes: having a developed glacial lake, a developing glacial lake, and without a glacial lake. We used topographical maps for the Nepal Himalayas and our surveyed data from 2004 for the Bhutan Himalayas.

3. Major Results Obtained by Fall 2011

3.1 Results from remote sensing analysis

In order to update and improve the glacial lake inventory for the Bhutan Himalayas, we used a new set of satellite data from the sensors on board the Advanced Land Observing Satellite (ALOS, '*Daichi*' in Japanese). With their high spatial resolution and their efficacy in making DEMs, ALOS-based satellite data are particularly desirable for investigating glacial lakes. The accuracy and methodology for delineating glacial lakes are confirmed with field survey data (Ukita *et al*., 2011). A preliminary inventory was released in February 2011. An outline of the remote sensing analysis is described by Tadono *et al*. (2012) in this issue. We intend to complete the inventory covering the Bhutan Himalayas, including the Tibetan side, within this project.

3.2 Results from field observations

We have conducted three field trips to the Mangde-Chhu basin since the project was launched. We conducted bathymetric surveys for nine glacial lakes in the basin (Lakes Zanam A, B, C, D, F and G, an unnamed one, and Lake Metatshota in Fig. 3). Five other lakes in the Lunana and Gangju La regions were also surveyed. Figure 5 shows our bathymetry of Lake Zanam C, which was identified as a potentially dangerous lake in our preliminary analysis (Fig. 6), whereas it had not been selected as a potentially dangerous glacial lake (PDGL) in the previous ICIMOD report (Mool *et al*., 2001b). Our analysis using ASTER data was unable to estimate how the shoreline would change if the lake water were drained; the bathymetry, which was obtainable only by an

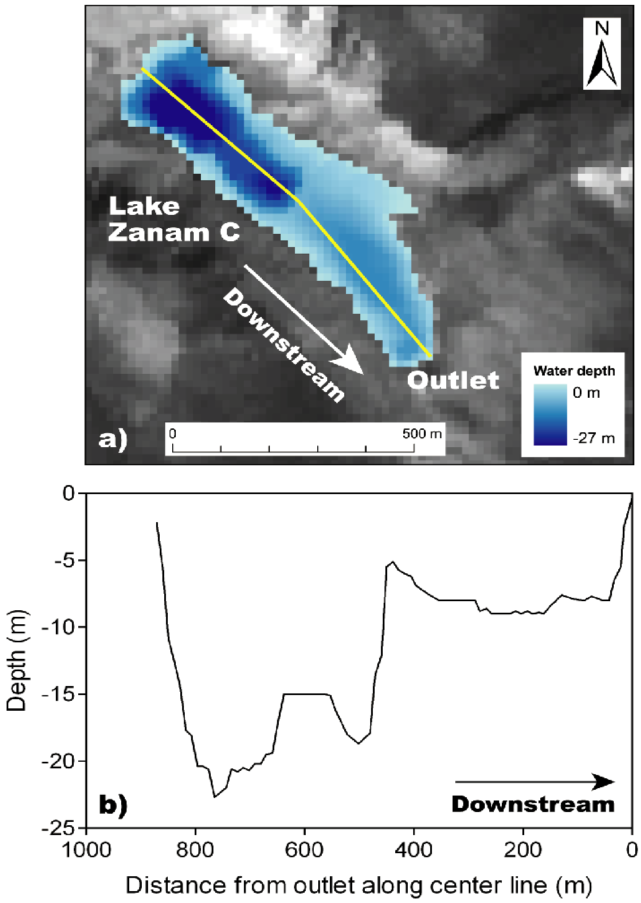

Fig. 5 The bathymetry of Lake Zanam C. The longitudinal depth profile in (b) is depicted along the yellow line in (a).

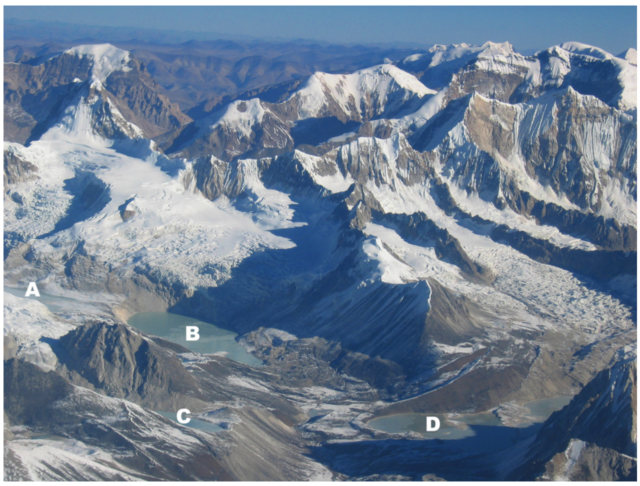

Fig. 6 The Zanam region of the Mangde Chhu headwaters, from the sky. Alphabetical letters denote lakes in the region (see also Fig. 2). Photograph courtesy of Y. Konagaya (Kawasaki Geological Engineering Co. Ltd.).

in-situ survey, was our primary information to evaluate the flood water volume if a GLOF occured. The measurement revealed that the flood water volume would be constrained by the shallow water depth on the downstream side and suggested that Lake Zanam C was fairly safe.

We performed geophysical explorations as well to confirm the structure of the damming moraine because the existence of ice within the moraine dam can significantly alter the strength of the dam (Hambrey *et al*., 2008). The detailed results are shown by Ohashi *et al*. (2012) in this issue.

In addition to the GLOF issue, changes in glaciers are matter of debate in the Himalayan region (Cogley *et al*., 2010). In particular, observational evidence is scarce in the Bhutan Himalayas. We updated terminus positions and volume changes in small glaciers along the research route (SG in Fig. 3), which had been surveyed at the end of the 20th century (Naito *et al*., 2006). All of the surveyed glaciers showed obvious retreat and shrinkage. The details are described by Naito *et al*. (2012) in this issue.

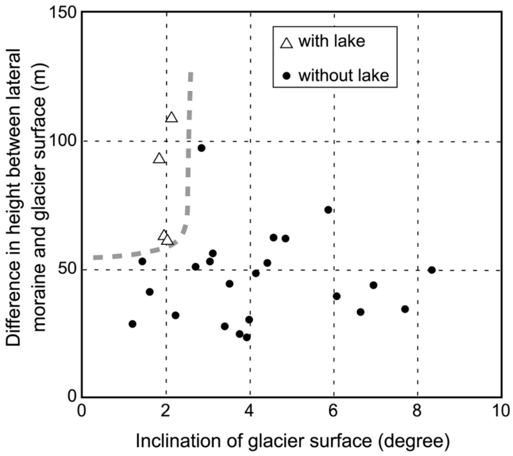

Fig. 7 A scatter diagram showing the difference in height between a lateral moraine and the glacier surface (vertical axis) plotted against the glacier surface inclination (horizontal axis) for Himalayan debris-covered glaciers. White triangles and solid circles indicate glaciers with glacial lakes and glaciers without glacial lakes, respectively. The gray dashed line represents the boundary between glaciers with and without glacial lakes among Himalayan debris-covered glaciers. The figure is modified from Sakai and Fujita (2010).

3.3 Formation conditions of Himalayan glacial lakes

Besides the field observational data, the analysis of which will take time, we worked on topographic maps and remote sensing data to depict which parameters have determined the formation of glacial lakes. Sakai and Fujita (2010) clarified that the formation conditions of a glacial lake could be clearly expressed in terms of the inclination of the glacier surface and the amount of surface lowering on the debris-covered area of the glacier since the Little Ice Age (LIA) in the Nepal and Bhutan Himalayas (Fig. 7). The figure shows that debris-covered glaciers with a growing or developed glacial lake (longitudinal length > 1 km) have gentler inclinations and larger surface lowering from the LIA than do glaciers without glacial lakes. This relationship can be explained by the contribution of calving of the terminus by ablation at supraglacial ponds and by glacier ice dynamics. The formation of a terminal glacial lake results in reduced compression in the lower part of the glacier, as the glacier ice at the terminus receives no pressure from adjacent ice or the terminal moraine. This reduced compression results, in turn, in reduced emergence velocity (weak uplifting of the glacier surface), leading to further lowering of the glacier surface. Hence, glacial lake formation involves a positive feedback to the lowering of the glacier surface, meaning that glacial lakes form in association with relatively large amounts of surface lowering. Furthermore, glacial lakes contribute to the disintegration of the glacier terminus and acceleration of the rate of lowering of the glacier surface. An overview with respect to glacial lake formation is given by Sakai (2012) in this issue.

3.4 A flood event from the Tshojo Glacier in 2009

On 29 April 2009, an unusual water discharge occurred from the Lunana region. The source of the discharge was the Tshojo Glacier, 15 km in length and 20 km^2 in area. This typical debris-covered glacier is one of the biggest glaciers in the Bhutan Himalayas. Local citizens, who had experienced the 1994 GLOF, were thrown into a commotion by this event, though there was no damage. However this disturbance was the first such experience after the 1994 GLOF. A discharge meter in the Pho Chhu suggested the flood water volume to be more than 0.5 million m^3.

We carried out field surveys after the event in 2009

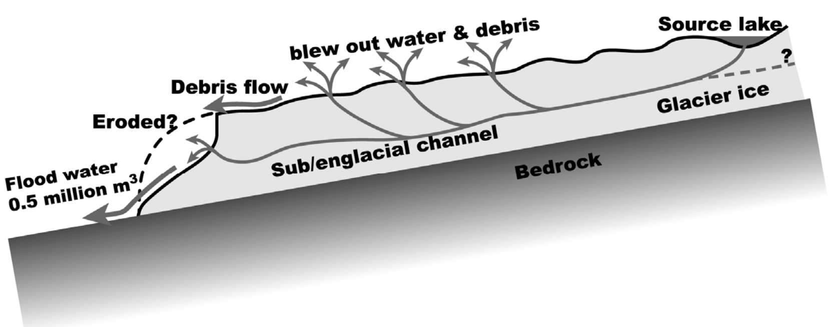

Fig. 8 Schematic profile of the Tshojo outburst event in 2009.

and 2010 and found deeply eroded channels on the glacier and the fan shaped deposit in front of the outlet. These characteristic features suggest that flood water with a large amount of debris was transported from upstream through subglacial and/or englacial channels (Fig. 8). In addition an analysis of multi-temporal remote sensing images revealed the abrupt disappearance of a supraglacial lake located 5.5 km upstream from the outlet. Yamanokuchi *et al*. (2011) estimated the total volume of the flood at 1.5 million m^3 based on ALOS PRISM DSMs, which were taken before and after the flood event. This volume is three times more than the estimate from the downstream river gauge (0.5 million m^3). This is equivalent to a water level lowering of 12.5 m. We simply estimated, on the other hand, that the water level lowering of the lake would have been 4.3 m from the lake dimensions (0.118 km^2) and flood volume (0.5 million m^3). Despite the remaining discrepancy with respect to volume, we can conclude that this vanished lake was a source of this small GLOF event. More details on this event are described in Komori *et al*. (2012) in this issue.

3.5 Flood simulation and hazard map

The actual GLOF impact on the residential areas downstream of the Mangde Chhu River basin was simulated by a numerical analysis with bathymetric profiles, ALOS-based DEM and hydraulic aspects. We assessed breach potentials of several glacial lakes in the basin, including PDGLs nominated by ICIMOD (Mool *et al*., 2001b) by using the same soil parameters of the reproduced breach scenario of the Lugge Glacial Lake moraine dam in the Lunana region, which burst in 1994. Due to the wide crest and gentle slope of the moraine dams, consequently, sediment transportation hardly accelerates in the condition of normal inflow, and the breach potential is comparatively lower than that of the Lugge Glacial Lake.

Lake Metatshota is the largest glacial lake in the Mangde Chhu River basin and is surrounded by an undulating moraine. Although the breach potential of the damming moraine is comparatively low as mentioned above, we further simulated how the flood wave would propagate along the river in the case of an outburst. The total flood volume and breach peak discharge of Lake Metatshota are estimated to be 18 million m^3 and 2,750 m^3s^{-1} respectively, when the moraine dam drastically starts to breach with an inflow to the lake exceeding 50 m^3 s^{-1}. Assuming this probable large-scale scenario, in which an outburst releases the lake water immediately, the flood wave from Lake Metatshota would arrive at Bjizam village, 62 km downstream of the lake, within three hours. The flood would rise to a peak discharge of 2,000 m^3 s^{-1} in a moment. Under this condition, the lower terrace plain of the village would be affected and the National Highway across the river would possibly be damaged (Fig. 9). The detailed results are described by Koike and Takenaka (2012) in this issue.

3.6 Landslide mapping

Detection of landslide slopes is essential for hazard assessment of GLOFs because the occurrence of GLOFs may reactivate potential landslides through river bank erosion. We delineated landslide distribution in the Mangde Chhu River basin through interpretation of satellite images and field surveys. We topographically classified the detected landslides into two types; deep-seated gravitational deformation (DSGD) and slides. Mountain slopes in this area are widely occupied by old landslides, some of which are over several km in width. Deep-seated landslides located at undercut slopes along the river may be reactivated by GLOFs and make slopes unstable. Details are described by Higaki and Sato (2012) in this issue.

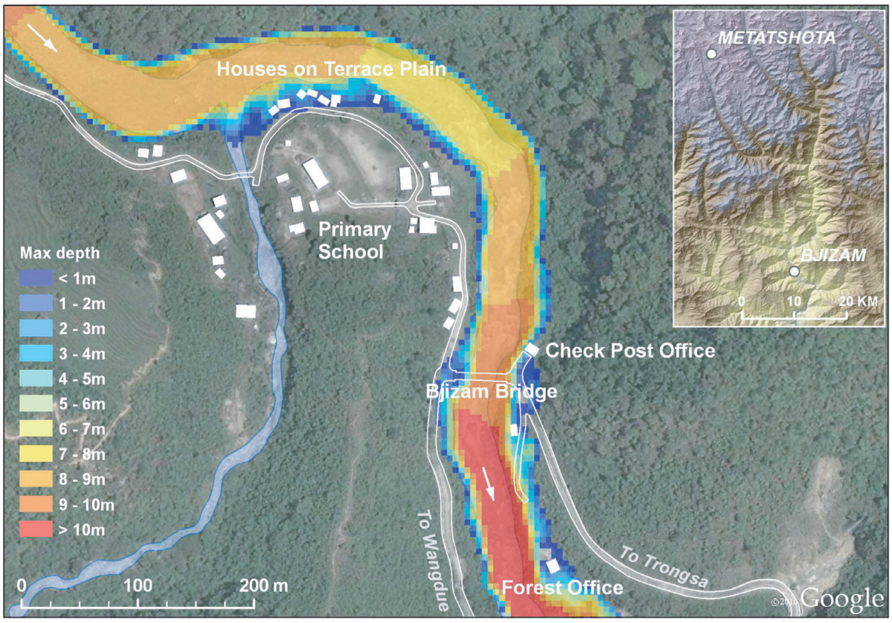

Fig. 9 Simulated flood depth at Bjizam Village in the Mangde Chhu River basin. The village is located 62 km downstream from Lake Metatshota (Koike & Takenaka, 2012).

Table 1 Technology transfer in the project (as of the end of October 2011).

Type of training	Location	Subject	Trainee No.	Trainer	Period
Training in Bhutan					
On the job training	Upper Mangde Chhu basin	Glaciological surveys	4	Process Group	20 weeks
		Land and lake surveys	3		
		Electric resistivity surveys	2	ESS	5 weeks
	Lower Mangde Chhu basin	Landslide surveys	3	Assessment Group	5 weeks
		Active fault surveys	2	Dr. Kumahara, Gunma Univ.	3 weeks
		Electric resistivity surveys	3	ESS	5 weeks
		Groundwater exploration	2	ESS	2 days
Indoor training	DGM office	Satellite data analyses	10	Satellite Group	3 weeks
		Flood analyses with GIS	5	ESS	3 weeks
		Soil testing in geotech laboratory	1	Mr. Umemura, Nihon Univ.	3 weeks
Training in Japan					
Short-term training (conducted by this project)	Tsukuba	Satellite data analyses	1	Satellite Group	1 week
	Tokyo	Flood analyses with GIS	1	ESS	1 week
	Koriyama	Geotec laboratory	1	Mr. Umemura, Nihon Univ.	1 week
	Tokyo	Electric resistivity survey	2	ESS	1 day
Long-term training (ordinary plans in JICA technical cooperation)	Tsukuba	RS/GIS and Flood analyses	2	ICHARM	1month
	Tsukuba	Flood analyses and planning	2		1month
Field excursions	Tohoku and Kanto regions	Mountain, earthquake and snow hazard and their mitigation works	4	Assessment Group	6 weeks
Activities in academic society	Several cities in Japan	Presentation of research progress	5	All project members	10 days

ESS: Earth System Science Co.,Ltd., DGM: Department of Geology and Mines, Bhutan, ICHARM: International Center for Water Hazard and Risk Management. JICA: Japan International Cooperation Agency.

3.7 Technology transfer

We are assisting our Bhutanese counterparts in enhancing their ability to cope with GLOF-related issues. Within three years several ‘on the job training’ sessions (OJTs) both in the field and indoors were carried out (Table 1). These activities are approximated at eighty man-months as of the end of October 2011. In addition, several training sessions in Japan with field excursions and attendance of scientific conferences were conducted for nine Bhutanese counterparts (Table 1).

One of the most important OJTs was field observations and related logistics through our field surveys. Bhutanese counterparts already have good experience with respect to mountain fields so they could immediately acquire the techniques; for example how to conduct bathymetric surveys, glacier surveys, geophysical explorations on damming moraines and meteorological observations. Although it is important to learn how to analyze the data obtained, this is an ongoing effort in the project. Further instructions on how to prepare and analyze satellite remote sensing data were given and in fact a few Bhutanese counterparts took charge of delineating glacial lakes in the specified basin (Tadono *et al*., 2012). Training sessions on flood simulation and hazard mapping are also planned within this project period. Exchange of information with respect to project progress was performed through joint coordination committees and science workshops, which were held in March of 2009 and 2010.

4. Conclusions

The potential risks from Himalayan glacial lakes have to be evaluated in an appropriate manner because feasible allocation of finite financial and human resources is crucial to dealing with the GLOF hazard issue. In this article we gave an outline of our interdisciplinary project for GLOFs in the Bhutan Himalayas. We established an up-to-date glacial lake inventory in the Bhutan Himalayas based on ALOS data (Ukita *et al*., 2011). We also re-evaluated PDGLs in the region based on the inventory. Bathymetric surveys, geophysical explorations and meteorological observations were conducted in the Zanam region, at the headwaters of the Mangde-Chhu River basin, to evaluate the potential risk of GLOFs and the possible amount of flood water discharge in the case of a GLOF. Based on these field data, we performed flood simulations and then constructed a hazard map along the river, in which the danger of landslides along the river was taken into account to evaluate the vulnerability of neighboring slopes.

On the basis of predictions on future glacial lake evolution (Sakai & Fujita, 2010), a glacial lake monitoring system using satellite data from all-weather synthetic aperture radar such as ALOS-PALSAR, TerraSAR-X and ALOS-2 (Suzuki *et al*., 2011) would be helpful to Himalayan countries. In the context of GLOF prevention, such a system can be used to single out lakes that need preventive work. This also provides valuable information for future watershed disaster management planning and land development downstream. In terms of prevention, lakes in early stages (smaller lakes) are relatively easier to deal with cost-effectively, because their potential flood volumes are less than those of well developed large lakes, even if artificial expansion of the outlet triggers an outburst.

For prevention, the most effective method is to lower the water level of lakes by draining. This, however, is expensive and thus impractical, as the potentially dangerous lakes in the Himalayan countries are typically located in remote and high altitude areas. It would be highly desirable to build early-warning systems for taking GLOF countermeasures, which could alert residents in the downstream regions.

Although our project is being conducted only in the Bhutan Himalayas due to institutional constraints, we believe that the course of our approach to this issue is adaptable to other Himalayan countries. The success of this project might be confirmed when GLOF assessments in other basins are performed by Bhutanese researchers.

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References

Ageta, Y., S. Iwata, H. Yabuki, N. Naito, A. Sakai, C. Narama and Karma (2000) Expansion of glacier lakes in recent decades in the Bhutan Himalayas. *International Association of Hydrological Sciences*, Publication No. 264 (Symposium at Seattle 2000 - Debris-covered glacier): 165-175.

Bolch, T., M.F. Buchroithner, J. Peters, M. Baessler and S. Bajracharya (2008) Identification of glacier motion and potentially dangerous glacial lakes in the Mt. Everest region/Nepal using spaceborne imagery. *Natural Hazards and Earth System Sciences*, 8: 1329-1340.

Clague, J.J. and S.G. Evans (2000) A review of catastrophic drainage of moraine-dammed lakes in British Columbia. *Quaternary Science Review*, 19(17-18): 1763-1783.

Cogley, J. G., J. S. Kargel, G. Kaser and C. J. van der Veen (2010) Tracking the source of glacier misinformation. *Science*, 327: 522.

Fujita, K., R. Suzuki, T. Nuimura and A. Sakai (2008) Performance of ASTER and SRTM DEMs, and their potential for assessing glacial lakes in the Lunana region, Bhutan Himalayas. *Journal of Glaciology*, 54(185): 220-228.

Fujita, K., A. Sakai, T. Nuimura, S. Yamaguchi and R. R. Sharma (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: 045205.

Hambrey, M.J., D.J. Quincey, N.F. Glasser, J.M. Reynolds, S.J. Richardson and S. Clemmens (2008) Sedimentological, geomorphological and dynamic context of debris-mantled glaciers, Mount Everest (Sagarmatha) region, Nepal. *Quaternary Science Reviews*, 27: 2361-89.

Higaki, D. and G. Sato (2012) Erosion and sedimentation caused by Glacial Lake Outburst Floods in the Nepal and Bhutan Himalayas. *Global Environmental Research*, 16: 71-76.

Iwata, S., Y. Ageta, N. Naito, A. Sakai, C. Narama and Karma (2002) Glacial lakes and their outburst flood assessment in the Bhutan Himalaya. *Global Environmental Research*, 6: 3-17.

Koike, T. and S. Takenaka (2012) Scenario analysis on risks of glacial lake outburst floods on the Mangde Chhu River, Bhutan. *Global Environmental Research*, 16: 41-49.

Komori, J., T. Koike, T. Yamanokuchi and P. Tshering (2012) Glacial lake outburst events in the Bhutan Himalayas. *Global Environmental Research*, 16: 59-70.

Mool, P.K.,S.R. Bajracharya and S.P. Joshi (2001a) *Inventory of Glaciers, Glacial Lakes and Glacial Lake Outburst Floods. Monitoring and Early Warning Systems in the Hindu Kush-Himalayan Region Nepal*. ICIMOD and UNDP-ERA-AP.

Mool, P.K., D. Wanda, S.R. Bajracharya, K. Kunzang and S.P. Joshi (2001b) *Inventory of Glaciers, Glacial Lakes and Glacial Lake Outburst Floods. Monitoring and Early Warning Systems in the Hindu Kush-Himalayan Region Bhutan*. ICIMOD and UNDP- ERA-AP.

Naito, N., Y. Ageta, S. Iwata, Y. Matsuda, R. Suzuki, Karma and H. Yabuki (2006) Glacier shrinkages and climate conditions around Jichu Dramo Glacier in the Bhutan Himalayas from 1998 to 2003. *Bulletin of Glaciological Research*, 23: 51-61.

Naito, N., R. Suzuki, J. Komori, Y. Matsuda, S. Yamaguchi, T. Sawagaki, P. Tshering and K.S. Ghalley (2012) Recent glacier shrinkages in the Lunana region, Bhutan Himalayas. *Global Environmental Research*, 16: 13-22.

Ohashi, K., T. Koike, S. Takenaka and J. Umemura (2012) Study on applicability of electric sounding for interpretation of internal structure of glacial moraines. *Global Environmental Research*, 16: 51-58.

Richardson, S.D. and J.M. Reynolds (2000) An overview of glacial hazards in the Himalayas. *Quaternary International*, 65/66: 31-47.

Röhl, K. (2008) Characteristics and evolution of supraglacial ponds on debris covered Tasman Glacier, New Zealand. *Journal of Glaciology*, 54: 867-880.

Sakai, A. (2012) Glacial lakes in the Himalayas: A review on formation and expansion processes. *Global Environmental Research*, 16: 23-30.

Sakai, A. and K. Fujita (2010) Formation conditions of supraglacial lakes on debris-covered glaciers in the Himalayas. *Journal of Glaciology*, 56(195): 177-181.

Sakai, A., K. Nishimura, T. Kadota and N. Takeuchi (2009) Onset of calving at supraglacial lakes on debris covered glaciers of the Nepal Himalayas. *Journal of Glaciology*, 55: 909-917.

Suzuki, S., Y. Kankaku and Y. Osawa (2011) Development status

of PALSAR-2 onboard ALOS-2, Proceedings of SPIE, 8176 (in press).
Tadono, T., S. Kawamoto, C. Narama, T. Yamanokuchi, J. Ukita, N. Tomiyama and H. Yabuki (2012) Development and validation of new glacial lake inventory in the Bhutan Himalayas using ALOS 'DAICHI.' *Global Environmental Research*, 16: 31-40.
Tashi, T. (1994) Preliminary report on the investigation of glacial lakes at Pho Chhu source and the assessment of food affected areas in Lunana. Thimphu, Royal Bhutanese Government.
Ukita, J., C. Narama, T. Tadono, T. Yamanokuchi, N. Tomiyama, S. Kawamoto, C. Abe, T. Uda, H. Yabuki, K. Fujita and K. Nishimura (2011) Glacial lake inventory of Bhutan using ALOS data: Part I. Methods and preliminary results. *Annals of Glaciology*, 52(58): 65-71.
Wang, X., S.Y. Liu, W.Q. Guo and J. Xu (2008) Assessment and simulation of glacier lake outburst floods for Longbasaba and Pida Lakes, China. *Mountain Research and Development*, 28: 310-317.
Yamada, T. (1998) *Glacier Lake and Its Outburst Flood in the Nepal Himalaya*. Monograph No. 1, Data Center for Glacier Research, Japanese Society of Snow and Ice, 96 p.
Yamada, T., N. Naito, S. Kohshima, H. Fushimi, F. Nakazawa, T. Segawa, J. Uetake, R. Suzuki, N. Sato, Karma, I.K. Chhetri, L. Gyenden, H. Yabuki and K. Chikita (2004) Outline of 2002 - research activities on glaciers and glacier lakes in Lunana region, Bhutan Himalayas. *Bulletin of Glaciological Research*, 21: 79-90.
Yamanokuchi, T., T. Tadono, J. Komori, S. Kawamoto and N. Tomiyama (2011) Temporal monitoring of supraglacial lakes on Tshojo Glacier at Bhutan. IEEE International Geoscience and Remote Sensing Symposium, Vancouver, Canada, Paper No. 3830.

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