Japan Geoscience Union Meeting 2011
(May 22-27 2011 at Makuhari, Chiba, Japan)

HDS025-01 Room:103 Time:May 22 09:30-09:45

Glacial Lake Inventory of Bhutan using ALOS Data: Methods and Preliminary Analysis

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The Advanced Land Observing Satellite (ALOS) is a relatively new satellite. Its optical sensors are capable of making high-resolution digital surface models (DSM). For the first time, the task of constructing a regional-scale inventory for glacial lakes based on ALOS data has been undertaken. This study presents the data processing methods and the results of validation and analysis on the ALOS-based glacial lake inventory of Bhutan in the Himalayas. The analysis based on GPS measurements taken at Metatshota Lake in the Mangde Chu sub-basin, one of the glacial lakes assessed as potentially dangerous for flooding, shows a validation estimate of 9.5 m for the location of the ALOS-based polygon with the RMS of 6.9 m. A comparison with digitized data from the International Centre for Integrated Mountain Development (ICIMOD) illustrates that a significant amount of improvement in positioning and in evaluating terrain changes can be achieved using ALOS data. Preliminary analysis on the glacial lakes in four sub-basins, Mo Chu, Pho Chu, Mangde Chu, and Dangme Chu, reveals that the frequency distribution of lake sizes biases towards smaller lakes. Glacial lakes in the size of 0.01-0.05 km2 account for approximately 55% in number and occupy 13% of the area. Together our results demonstrate the usefulness of high-resolution ALOS data with accurate DSMs in studying glacial lakes. High priority must be given to continuously improving and updating glacial lake inventory with high-resolution satellite data.

Keywords: GLOF, ALOS, inventory, Bhutan, Himalayas

Japan Geoscience Union Meeting 2011
(May 22-27 2011 at Makuhari, Chiba, Japan)

HDS025-02 Room:103 Time:May 22 09:45-10:00

Free Public Access on Glacier Lake Inventory in the Bhutan-Himalayas using ALOS Data

Chiyuki Narama[1*], Takeo Tadono[2], Jinro Ukita[3], Tsutomu Yamanokuchi[4], Sachi Kawamoto[4], Nobuhiro Tomiyama[4], Hironori Yabuki[5], Koji Fujita[6], Kouichi Nishimura[6]

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We started to make a new glacier lake inventory for the Bhutan-Himalayas, which have resulted from a Bhutan glacier lake studies in JICA/JST project (2009-2011). In the Himalayas, glacier lake outburst floods (GLOFs) have occurred once or twice per decade. Because GLOFs cause serious damage in downstream regions, the inventory shows the basic data of glacier lakes, and useful for disaster planning, prevention, and glacier lake studies in the world.

The present study is intended to generate pan-sharpened image using PRISM (2.5 m spatial resolution) and AVNIR-2 (10 m resolution) onboard ALOS, and extracted glacial lake manually. Glacial lakes in our definition are bodies of water that lay between the terminus of the mother glacier and the Little Ice Age moraine. Lakes located within 2 km of the Little Ice Age moraine down-valley are also included to take into account a possible flooding event with multiple lakes being involved. In addition, supra-glacial lakes on debris-covered glaciers are included. Finally, we set 0.01 km2 as the minimum lake size considering small lakes contribute a less amount of GLOFs risk. In present, a sample of the glacial lake inventory is preparing to open free access via. online, will be released on March 2011. It is including glacial lakes ID, satellite paths, observation date, latitude, longitude, watershed name, area, length, width, altitude, direction, type of glacial lakes, and ICIMOD ID which will be consisted with the glacial lake polygon information. This presentation introduces development of the inventory and opens to public on March 2011.

Keywords: Glacier lake, Inventory, ALOS, GLOF, Bhutan-Himalayas

Japan Geoscience Union Meeting 2011
(May 22-27 2011 at Makuhari, Chiba, Japan)

HDS025-03 Room:103 Time:May 22 10:00-10:15

Re-evaluation of potential of glacial lake outburst flood in the Himalayas

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Hazard of glacial lake outburst flood (GLOF) is an urgent environmental issue in the Himalayan countries such as Bhutan and Nepal. The GLOFs have frequently occurred since the 1960s, accompanied with shrinkage of glaciers and attendant expansion of glacial lakes. A previous study has reported that potentially dangerous glacial lakes existed 20 in Nepal and 24 in Bhutan. No obvious criteria, however, is not shown so far. In addition, some ”real dangerous” glacial lakes, which have been pointed out by several field researchers, were not listed in the previous inventory.

We attempt to re-evaluate potential risk of GLOF by using ASTER images and digital elevation models (DEMs). Relative angles of surrounding topography against a lake surface are calculated. By adopting a threshold of 10 degree, a place surrounding glacial lake, where field researchers have felt as dangerous, is successfully marked. In addition, we validate the threshold angle by assessing the pre-GLOF lakes by Hexagon KH-9 satellite images and its DEM. We re-evaluate the 44 dangerous glacial lakes in Bhutan and Nepal.

Keywords: Himalayas, Glacial lake, ASTER, Hexagon, DEM

Japan Geoscience Union Meeting 2011
(May 22-27 2011 at Makuhari, Chiba, Japan)

HDS025-04 Room:103 Time:May 22 10:15-10:30

Formation condition of debris-covered glaciers in the Bhutan Himalaya derived by satellite data

Hiroto Nagai[1*], Koji Fujita[1], Takayuki Nuimura[1]

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Debris-covered glaciers are widely distributed along the Himalayas. It is well known that insulation effect of debris mantle and heterogeneous topography make response of the debris-covered glaciers to climate change complex. Furthermore, glacial lakes, which have often occurred outburst flood and thus threat Himalayan countries, are formed at the termini of debris-covered glaciers. It is little understood, however, what kinds of gepmorphological and climatic environment determine the glacier termini as debris-covered or debris-free. In this study we describe geomorphological conditions which determine whether glacier termini are covered by debris as well as their shape in the Bhutan Himalaya using remotely sensed satellite data.

We first delineate glaciers and surrounding slopes using AVNIR2 visible ortho-rectified images obtained by ALOS. Debris-covered areas are defined by a normalized snow index derived by ASTER data. We secondly analyze slope angle and aspect of the glaciers and the surrounding slopes using ASTER-GDEM by assuming that the debris mantle is supplies from the slope steeper than 40^o. We also estimate surface temperature distribution using thermal infrared data of ASTER because freeze-thaw activity at the bedrock should produce debris mantle.

We delineate more than 1000 glaciers in the Bhutan Himalaya including north facing glaciers on the Tibetan slope. Spatial analysis show that the debris-covered glaciers have five times larger area of steep slopes than the debris-free glaciers. Surface temperature distribution indicates that the surface exceeding 0 ^{o}C is found in the south-facing steep slopes even in winter season. We find a significant positive correlation between the area of steep slopes exceeding 0 ^{o}C and the area of debris-covered surface. In addition, ablation area of the south facing debris-covered glaciers is fully covered by debris mantle, which should be supplied from the widely distributed south-facing steep slopes, while the north-facing glaciers have an elongated debris-covered area along flow line of the glaciers, whose debris mantle seems to be supplied from very limited but south-facing steep slopes within the glacier catchment. Our analyses suggest that the spatial distribution of south-facing steep slopes determine the extent and shape of debris-covered area in the Bhutan Himalaya.

Keywords: Debris-covered glacier, Freeze-thaw activity, Bhutan, Himalaya, ALOS, ASTER

Japan Geoscience Union Meeting 2011
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HDS025-05 Room:103 Time:May 22 10:45-11:00

Possibility of the glacial lake outburst floods in the Hongu Valley, eastern part of Nepal

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During the past several decades in the Mt. Everest and Makalu-Barun national parks of Nepal, 24 new glacial lakes have formed and 34 major lakes have grown substantially as a result of climate change and regional warming trends (Bajracharya et al. 2007). Recent satellite analyses have suggested that at least 12 of the new or growing lakes within the Dudh Kosi watershed, 9 of which are located in the remote Hongu valley of Makalu-Barun National Park, are "potentially dangerous" based on remote sensing that documented their rapid growth over the past several decades (Bajracharya et al. 2007; Watanabe et al. 2009). However, in spite of the large amount of national and international media attention recently generated by these new and/or growing lakes, relatively little was known about these lakes because of their extreme remoteness and difficulty of access.

Chamlang Pokhari, listed as West Chamlang in Table 1 by Bajracharya et al. (2007), was considered by many to be a "dangerous" lake based on satellite image analysis. It is also considered to be dangerous by local peaple as well. While it was observed that there is indeed considerable overhanging ice above the lake that could be dislodged and cascade into the lake that in turn caused a surge, the length and surficial roughness of the region between the lake and the terminal moraine (i.e., the region below the meltwater ponds that can be seen to the left) suggests that any surge would most likely be buffered and repelled.

In 2009 we carried out intensive investigation on the Chamlang Pokhari at the western foot of the Peak Chamlang in the remote Hongu valley of Makalu-Barun National Park of East Nepal. Geomorpholocal observations and bathymetric surveys at around the Chamlang Pokhari were carried out in Novenber 2009 during the ice-melted period. The depth was confirmed continuousely on an line using echo sounding with GPS positioning.

The bathymetric map shows that the current lake is about 550 m in width (north-south) and about 1,650 m in length (east-west). The lake was most probably very small in 1962 when a climbing expedition team from Hokkaido University scaled the summit of Mt. Chamlang. The lake area shown on the Schneider map (surveyed between 1955 and 1974) is roughly one-sixth of the current area. The bathymetric survey indicates that the maximum water depth is 87 m.

A survey around the terminal moraine was also carried out to reveal seapage of lake water from the moraine. The result showed that the glacier ice was grounding. The ice cliff at the terminus was in continual contact with lake water, and had drifted due to valley winds passing over the lake.

Keywords: glacial lake outburst flood, Nepal Himalaya, bathymetry, Makalu-Barun national park, Chamlang

Japan Geoscience Union Meeting 2011
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HDS025-06 Room:103 Time:May 22 11:00-11:15

Overview on the risk minimization project in Thorthormi glacial lake

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With the financial assistance from the UNFCCC, this project mainly focuses on the risk minimization for Glacial Lake Outburst Flood (GLOF) in Punakha Wangdi valley along Pho Chu river. The project was designed with a budget of approximately 127 to130 million Ngultrum (equivalent to an Indian Rupe) with a co financing scheme from the Austrain Government and WWF Bhutan.

The overall objective of the project was to lower the lake water level in Thorthormi lake by 5 m which according the technical mitigation plan drawn up in collaboration with the Austrain experts was a safety level to prevent a catastrophic GLOF in the future. The whole project was formulated for four years period with four working seasons per year with atleast 300 workers in each working season. The team adopted a simple method of lowering the lake water level which basically is deepening and widening the natural existing outlet channel. No big machineries were used for fear of disturbing the surrounding unstable moraine walls separating the lakes.

The project was initiated in 2008 by carrying out an engineering and safety plan which was implemented in the first year after a technical consultation with the GEF technical team. The real excavation work on the channels started only in 2009. The progress for each year for the past two years (2009 and 2010) are given in the following section.

After two years of excavation work only about less than 50% target has been achieved. Considering the overall target of 5 m reduction in lake level and also considering the time frame of the project which is another one more years to complete 4 years of the project, the project team feels that the project should be extended by another working season to enable the team to achieve the overall target of 5 m. The less achievement in terms of target was mainly due to unavoidable circumstances encountered by the team in course of the project implementation.

Keywords: GLOF, hazard mitigation, electrical resistivity tomography, glacial ice, United Nations Development Programme, Bhutan

Japan Geoscience Union Meeting 2011
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HDS025-07 Room:103 Time:May 22 11:15-11:30

Hazardous lake evaluation by the field survey in the Bhutan Himalaya

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In order to assess the possibility of GLOF hazard in the Bhutan Himalaya, we closely observed 15 lakes and roughly checked 12 lakes along the snow man trekking route, northern Bhutan under the JICA/JST project. There is not specific information over the last 10 years. However most of these lakes were observed by Iwata and Ageta (1998). In this presentation we will introduce summery of the field condition and preliminary result of the evaluation based on a modified glacial lake check sheet (Iwata, 2000). The field surveys for the evaluation were carried out in/around the lakes in 2009 and 2010 by the authors and tenth other Japanese and Bhutanese researchers. Especially, bathymetric survey achieved to obtain more reliable information for assessing the stability of the moraine dame and flood analyses. Most of the lakes in the Mangde Chhu basin show relatively stable aspect because gentle relief of the surrounding topography of the lake.

Keywords: GLOF, risk evauation, check sheet, bathymetric survey, Mangde Chhu

Japan Geoscience Union Meeting 2011
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HDS025-08 Room:103 Time:May 22 11:30-11:45

Geophysical Exploration on Moraine Dam in Bhutan Himalaya

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There are many glacial lakes formed by the retreat of the glacier in Bhutan Himalaya. In some of them, satellite image analysis indicates the danger of glacier lake outburst floods (GLOF). Assessment of damage by GLOF in these lakes is very important for disaster prevention. And, the internal information of the moraine dam, like the existence of dead ice, is essential for disaster prevention. In this survey, to estimate the internal structure of the moraine by using the resistivity and the S-wave velocity obtained by geophysical exploration and to examine the validity of these methods.

The resistivity of the ice body and debris was measured in a D type glacier as a prospect survey. These results are very important for estimating the internal information. As a result, it was recognized that there was no ice body inside the moraine when the resistivity value was less that 20k ohm-m. 2Delectric sounding was carried out on two moraines. (ZanamC glacier lake and Metatsota glacier lake). Consequently, it was presumed that an ice body did not exist in the moraine, because the measured resistivity value was less than 20k ohm-m. Moreover, the Microtremor array results on the Metatsota glacial lake became similar to the 2D electrical sounding results. For this reason, geophones were able to be deployed extensively in a wide plain. On the other hand, an excellent result was not obtained in the ZanamC glacial lake. For this reason, geophones were able to be deployed only locally in a rough terrain. The development of the method and analysis is a problem for future examination for terrain conditions like ZanamC Glacier Lake.

Keywords: glacier lake outburst floods (GLOF), moraine dam, 2Delectric sounding, Microtremor array, Dead ice

Japan Geoscience Union Meeting 2011
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HDS025-09 Room:103 Time:May 22 11:45-12:00

GLOF from debris covered glacier - a case study of 2009 Tshojo glacier-

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Major GLOF has not been reported since 1998 in the southern side of the Himalayan range. On the other hand, ca. 50,000 m3 unusual water discharge occurred in April 2009, from Tshojo Glacier, southern Lunana, Bhutan (Komori et al., JSNDS, vol.29). In this session, the authors will show some aspects and presumable phenomena when the flood occurred, based on the field survey around the lower part of the glacier.

There are following geomorphological and sedimentological features in the lower part of the glacier. 1) Elongate lobes of sediment which are lie over one another and formed by well sorted gravel and sand. 2) The lobe topographys break over surrounding old debris and bushes. 3) Upper reaches of the lobe topographies are interrupted abruptly. 4) Funnel shaped depression with few m ˜ ten m in diameter scattered in the apper reaches of the lobe topographys. The aspects 1) 2) and 3) 4) show that debris flow on the glacier occurred multiply and the debris flow blow out from intra- or sub- glacier ice as sand/gravel boiling respectively. Furthermore, glacial ice and dried up channel in the ice are exposed due to the water lowering of the supra-glacial lakes in the few kilometers upper reaches from the funnel shaped depression. Above mentioned aspects may explains that unusual water discharge was small GLOF from some supraglacial-lake(s) as the confined water/debris blowout. Such a phenomenon was reported from Ripmoshar Glacier 1991 GLOF (Yamada and Sharma, 1993; Fujiwara and Gomi, 1995). The source of 1977 GLOF in Mingbo Valley (Fushimi et al., 1985) in CORONA satellite photograph, eastern Nepalalso shows same condition of Tshojo GLOF. Hence, these outbursts are familiar phenomenon in the debris covered glacier.

Keywords: GLOF, D-type galcier, Supra-glacial lake, intra-glacier channel, debris flow, gravel boiling

Japan Geoscience Union Meeting 2011
(May 22-27 2011 at Makuhari, Chiba, Japan)

HDS025-10 Room:103 Time:May 22 12:00-12:15

Monitoring of supraglacial lakes on Tshojo Glacier by satellite data related to unusual flood event occurred in 2009

Tsutomu Yamanokuchi[1*], Takeo Tadono[2], Jiro Komori[3], Toru Koike[4], Sachi Kawamoto[1], Nobuhiro Tomiyama[1], Puntsho Tshering[5]

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Global warming have a serious effect on world cryosphere and it sometimes causes the retreat of glaciers and formation of glacier lakes at the terminus of glacier. This causes a sudden outburst flood called GLOF (Glacier Lake Outburst Flood). GLOF is serious issue at Himalayan countries and actually more than 20 people were dead by GLOF event occurred in 1994 at Bhutan. A recent example is that unusual flood event was occurred along Pho Chu in 29, April, 2009. Tshojo Glacier is located at the headwater of Po Chu River and the source of this outflow water, while there is no huge glacier lake at the terminus of this glacier. Instead of huge lake, there are several spraglacial lakes on the glacier surface and one of the supraglacial lake was disappeared after this outflow event from the interpretation result of ALOS / PALSAR data.

This study aims to reveal the relationship between unusual water outflow event and disappearance of supraglacial lake through temporal analysis of supraglacial lakes on the Tshojo Glacier by using time series satellite data. Both optical and microwave sensor data are used for analysis, which are ALOS /PRISM, ALOS / AVNIR-2, SPOT-2 / XS and PA, SPOT-5 / XS and PA for optical sensor and ALOS / PALSAR data for microwave sensor (SAR) data.

Also, we have done ground survey around Tshojo Glacier in the autumn of 2010 to figure out this outflow event.

Next, we will plan to analyze the temporal change of this small lake and if possible, estimation of lost water volume of disappeared lake using DSM data made from ALOS / PRISM triplet pair. Then, we also try to reveal the relationship between the disappearance of lake and outflow event through the combined study with field survey results.

This research was supported by JST-JICA, SATREPS (Science and Technology Research Partnership). ALOS / PALSAR data were provided through ALOS PI project (PI No.571).

Keywords: GLOF, Satellite, Supraglacial lake

Japan Geoscience Union Meeting 2011
(May 22-27 2011 at Makuhari, Chiba, Japan)

HDS025-11 Room:103 Time:May 22 12:15-12:30

Supra-glacial ponds and spatial temporal changes of glacier surface environment (Thermal resistance, NDWI, and glacier f

Takayuki Nuimura[1*], Akiko Sakai[1], Koji Fujita[1]

[1]Nagoya University

Glacier surface environments, such as debris thickness, ponds, channels, play a important role for local melting condition.
Debris thickness affects local mass balance because of its insulation effect. In additions, ponds and ice cliffs, which were widely distributed on the debris-covered area, absorbed heat as hot spot. Hence, spatial distribution and the temporal changes of those factors are important for glacier melting, which could cause to emerge of supra-glacial ponds and its expansion to glacial lakes.
In this study, we analyzed some factors (thermal resistance, NDWI, and glacier flow velocity), which could contribute to glacier melting, using ASTER and Landsat satellite imagery. We report the relation between area change of supra-glacial ponds and those factors. We will show the result in presentation.

Keywords: glacial lake, glacier, ASTER, Landsat, thermal resistance, NDWI

Japan Geoscience Union Meeting 2011
(May 22-27 2011 at Makuhari, Chiba, Japan)

HDS025-12 Room:103 Time:May 22 12:30-12:45

Study on the formation condition of glacial lakes in the Himalayas

Akiko Sakai[1*], Koji Fujita[1], Takeo Tadono[2], Takayuki Nuimura[1]

[1]Nagoya University, [2]Japan Aerospace Exploration Agency

The Himalayas contain many debris-covered glaciers, some of which have large glacial lakes at the terminus. These lakes have been growing in size since the 1950s and 1960s, giving rise to the potential hazard of glacial-lake outburst floods.

It was already clarified that glacial lake formed that those glaciers which surface slop is less than 2 degrees and glacier surface lowering since the Little Ice Age is larger than 60 m using topographical maps (Sakai and Fujita, 2010). In this study, glacier slopes and DGM are analysed using high accurate ALOS/PRISM(Advanced Land Observing Satellite/ Panchromatic Remote-sensing Instrument for Stereo Mapping) DEM (Digital Elevation Model). The study areas were Khumbu region in the Nepal Himalaya, Tibet and Bhutan Himalayas.

The result indicated that formation conditions of glacial lakes using ALOS/PRISM DEM were same with the analysis of topographical maps. It was also clarified that large glaciers tend to have large surface lowering and gentle slopes.

In the presentation we examine the result in terms of ablation processes of debris-covered glaciers.

Keywords: glacial lake, glacier, moraine, ablation

HDS025-13 Room:103 Time:May 22 14:15-14:30

Factors controlling scale and shape of the Himalayan debris-covered glaciers

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Debris-covered glaciers in the Himalayan region are classified into two types: glaciers having moraine dammed lake in its terminus and without lake. Understanding the critical conditions between these two types is very important not only for glaciological aspect but also for hazard mitigation with respect to glacial lake outburst flood. Previous statistical analyses reported that glacial lake should not be developed over the glacier whose surface inclination steeper than 2 degree and vice versa. However, no physical theory has been proposed to explain this tendency. Moreover, little is known what factors determine the surface inclination of the debris-covered glacier.

In this study, we examine influences of several factors (debris supply, scale of accumulation area, and profile inclination of bedrock etc) on the surface inclination of debris-covered glacier using a numerical glacier dynamics model. Simulation results indicate that surface inclinations and glacier lengths of the debris-covered glacier are strongly dependent on these factors. Our results help to understand why the Himalayan debris-covered glaciers show large variety in scale and shape even under the same climate condition and why the steep glacier does not have glacial lake in its terminus.

Keywords: Himalaya, Glacier lake, Debris-covered Glacier, Glacier form

Japan Geoscience Union Meeting 2011
(May 22-27 2011 at Makuhari, Chiba, Japan)

HDS025-14 Room:103 Time:May 22 14:30-14:45

Landslide distribution in Mangde-chu River basin, Kingdom of Bhutan

Go Sato[1*], Daisuke Higaki[2], Toru Koike[3], Jun Umemura[4], Tshering Penjore[5], Phuntsho Norbu[5], Jiro Komori[6]

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There are many glacial lakes in the upper basin of the Mangde-chu River in Bhutan. Detection of landslide slopes is essential for a hazard assessment of glacial lake outburst floods (GLOFs) along the river because the occurrence of a GLOF may reactivate potential landslides by river bank erosion. The authors mapped the landslide distribution in the Mangde-chu basin using satellite images interpretation to determine the nature and distribution of the landslide phenomena in the area.

In this presentation, we report the results of the landslide distribution mapping as follows:

1) The detected landslides are topographically classified into types such as deep-seated type, shallow type, and rock-creep type.

2) Freshly glaciated valleys are formed above 4,100 m of riverbed elevation of the Mangde-chu River. Many shallow-type landslides (surface slope failure) are distributed on the valley slope. In addition, some moraines are dissected by small landslides such as slumps.

3) Many deep-seated-type and rock-creep-type landslides are distributed on the lower parts of the slope along the Mangde-chu River from 4,100 to 2,550 m of its riverbed elevation. The shapes of the glaciated valleys from 4,100 to 3,770 m riverbed elevation are preserved, but these shapes have been dissected by deep-seated-type and rock-creep-type landslides.

4) Large-scale rock-creep-type landslides are distributed on the upper and lower parts of the slopes along the Mangde-chu River from 2,500 to 2,100 m of its riverbed elevation. However, the distribution of deep-seated-type landslides is limited to the lower parts of the slope.

5) Large-scale deep-seated-type and rock-creep-type landslides are distributed widely on the upper and lower parts of the slope under 2,100 m of riverbed elevation of the Mangde-chu River. Most of the settlements and farmland along the Mangde-chu River are distributed on the landslide slopes of the deep-seated type.

This study was carried as part of the "Study on GLOFs in the Bhutan Himalayas" supported by JST-JICA, SATREPS.

Keywords: Landslide, GLOFs, Bhutan

Japan Geoscience Union Meeting 2011
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HDS025-15 Room:103 Time:May 22 14:45-15:00

A social survey for GLOF disaster mitigation in Bhutan

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A social survey for GLOF was carried out in central Bhutan in May 2010 as a part of JICA/JST GLOF project. The survey was focused on the awareness and the measures to mitigate the disasters.

The survey areas were along Mangdechhu, the target area of the project, and along Pnatsangchhu and Bumthangchhu, the neighboring rivers of Mangdechhu. Interviews were done using questionnaires prepared for local governments, schools and community residents. The contents of questionnaires were such as population, disaster prevention policy, emergency communication network (only for local governments), annual income, communication measures (only for community residents) and history of disaster, disaster awareness for all cases.

Key findings of the survey include:

- Generally awareness of GLOF of community residents was high, but disaster prevention education, disaster prevention measures and building communication network were still not enough. This kept them anxious about the disasters.
- Particularly in downstream of Mangdechhu, southern Bhutan, the ownership of communication tools like radio or cell-phone was comparatively low, may be because of low income of local residents. And constructions of infrastructures such as road network and communication systems were poor. This made the area vulnerable for the disasters.
- On the other hand local government and residents of Punakha and Wangdi, that suffered 1994 GLOF, showed higher awareness of the disasters as well as infrastructures compared with the other areas.

Keywords: Bhutan Himalaya, glacial lake, flood, GLOF, disaster prevention, social survey

Japan Geoscience Union Meeting 2011
(May 22-27 2011 at Makuhari, Chiba, Japan)

HDS025-16 Room:103 Time:May 22 15:00-15:15

Basic concepts of disaster prevention for GLOF in the eastern Himalayas

Shuji Iwata[1*]

[1]Iwata, Shuji

Based on the 10 years experience working on glacial lakes in the Himalayas, mainly in Bhutan, I report a geomorphological view for risks of glacial lake outbursts and mitigation measures downstream areas. The study area covers eastern Nepal, Sikkim, Bhutan, and their north sides of the Himalayas in Tibet. In these areas many glacial lakes have appeared and therefore risks of GLOFs are increasing year by year.

1 Dangerous lakes and their outburst triggers

Two types of glacial-lakes and their triggers for outbursts are identified in the eastern Himalayas.

a) Circular lake type: Smaller glacial lakes with steep glaciers such as hanging glaciers. Glacial avalanches or ice-block falls are the most frequent cause occurring for outburst of the type circular lakes with steep glaciers such as hanging glaciers. In this case, prediction is very difficult because glacial avalanches and ice-fallings occur suddenly and unexpectedly.

b) Rectangular lake type: Moraine dam vulnerability is the second frequent cause for the type rectangular lakes, but only few cases were reported. Melting of ice-cores in the moraines and seepage through the moraines are thought to be triggers of the moraine failures. In this case, prediction may be possible by intensive geodetic and geological inspections of moraine dams, but vast cost and manpower should be needed.

2 Features of floods by glacial lake outbursts

1) Peak discharge of the GLOF is very high and sharp, but duration of the flood is short. 2) Water levels of the floods along the river course are the maximum just below the lake and decrease downstream. 3) The flood occurs along the distinct river course originated from the busted lake.

The most dangerous places by the GLOFs are areas along the river courses which originated from the GLOFed lakes, and areas located just below the lakes. These features are very different with floods caused by severe rain of the monsoon or cyclone.

3 Expected mitigation measures

1) Prediction of GLOFs (especially when) is very difficult or almost impossible. This prediction can not save economic losses, but only human lives.

2) Mitigation measures in the downstream areas along the river should be done. 2-1) Emergency alarm systems and evacuation schemes should be planned. 2-2) Controls of the local land use and moving of settlements and constructions may be needed.

Making of hazard maps is most urgent measure.

Keywords: glacial lake outburst floods, outburst forecast, risk assessment, mitigation measures

Japan Geoscience Union Meeting 2011
(May 22-27 2011 at Makuhari, Chiba, Japan)

HDS025-17 Room:103 Time:May 22 15:15-15:30

Impulse wave generated by glacier avalanches and its effect on GLOFs

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Landslides, rock falls, snow avalanches, and glacier calvings may generate large water waves in the glacial lakes. These tsunami-type waves, called as impulse waves, can cause GLOF due to run-up or even destruction of the moraine dams. Although a considerable number of general model studies exist, the prediction of impulse wave features remain challenging. Most general model studies provide an empirical equation for the maximum wave features in the slide impact zone. However, the wave height, wave amplitude, wave period, and wavelength at a specific location of the lakes have to be available to determine the effects of impulse waves on a dam.

In this study the generation and propagation of the impulse waves were investigated in a small channel experimentally and, then, numerical simulations were carried out not only for the small scale but also for the glacial lakes in Bhutan.

Keywords: Glacial lake, Glacier avalanche, Tsunami