Watershed risk assessment of GLOF in Bhutan - a case study in Mangde Chhu river-basin -

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1. INTRODUCTION

Glacial lake outburst floods (GLOFs) from moraine dams which cause water and sediment disasters are the serious threat to the security of human life, infrastructure and economy of the Himalayan countries. As for the Bhutan Himalaya, since Gansser[1)] brought down the glacial lakes in his pioneer works, various subsequent studies on GLOF mostly in the upper stream, i.e., inventory works and risk assessment[2)], calculation of expansion rate of lakes[3),4)], and hazard mapping for flood[5)] have been carried out in Bhutan, especially in responded to GLOF from Luggye Tsho (Tsho means 'lake') in 1994. However, geo-hydrological investigation for flood and sediment risk assessment in the middle and lower stream is also necessary, because landslide damming as well as landslide reactivation induced by river bank erosion during a GLOF causes sediment disasters.

Risk assessments for such multiple disasters in Bhutan were preliminary conducted only in the Pho Chhu (Chhu means 'river') basin[6)]. Hence, this paper aims to clarify the present status and risk factors of a GLOF in the upper and middle Mangde Chhu basin in central Bhutan that has not been investigated. The results are mostly obtained under the GLOF Research Project, which Nagoya University and Geological Survey of Bhutan, Ministry of Trade and Industry, Government of Bhutan have been conducting under the support of Japan Science and Technology Agency (JST) and Japan International Cooperation Agency (JICA).

2. GEOGRAPHICAL BACKGROUND

(1) Geographical setting

The Kingdom of Bhutan has an area of 40,000 km^2, with the population of approximately 700,000. The domain extends 300 km from east to west and 150 km from north to south with an altitude range from above EL. 7000 m of the Himalayan range (Great Himalaya) to several tens of m of the Indian plain (Fig. 1). The mean annual precipitation varies from hundreds of mm in the northern area to over 4000 mm in the southern rain forest that directly

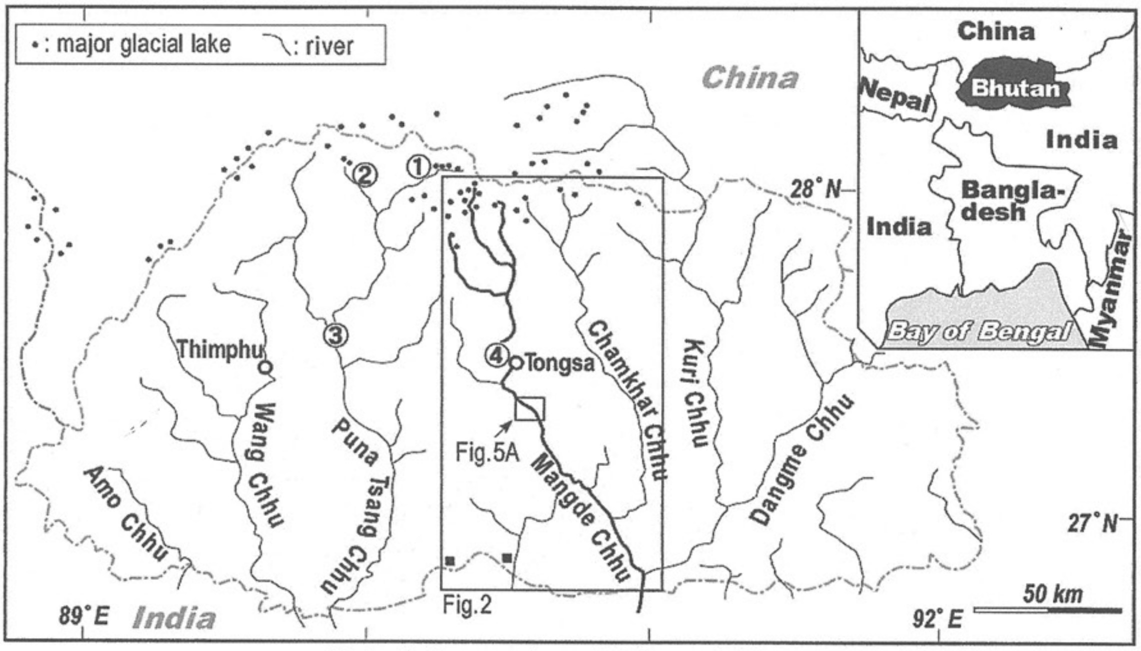


Fig.1 Study area and past GLOF events in Bhutan.
①: Lunana. ②:Tarina Lake. ③: Punakha. .④: Bjeezam.

receives dense vapor from the northern Indian Ocean.

(2) Topography and land use of the Mangde Chhu basin

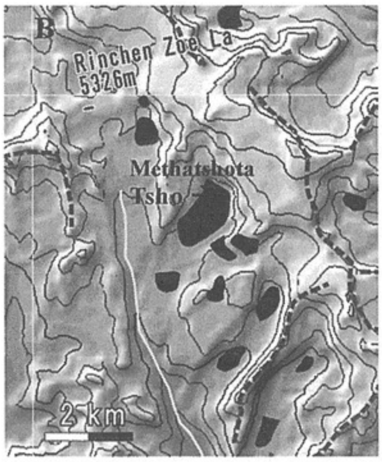
a) Topography

Mangde Chhu is one of the tributaries of Brahmaputra River, with 240 km in length. The river flows down ca. 160 km from EL. 7300 m of the headwater to EL. 100 m at the border of India with river bed gradient of 1/10~1/100, which correspond to the upper two-third of Mangde Chhu. The riverbed profile shows a step around Trongsa, about 100 km up the river from the border of India. Such a step of riverbed profile can also recognized in other major rivers in Bhutan, except Kuri Chhu. Most of the steps in these rivers have several accumulation terraces. However, the river terraces along Mangde Chhu are partially distributed small and few. Most of the valley shows V-shape up to EL. 3500 m, then glaciated U-shape valley above EL. 3800~3900 m (Fig2-a).

Present snouts of debris-covered type and debris-free type glaciers exist around EL. 4600 and 5000 m, respectively, under snow accumulation during summer monsoon. Some glacial lakes with the possibility of outburst are dammed by little ice age moraines. Most of these glacial lakes appeared and expanded before 1990's at EL. 4800~5300 m.

b) Land use

Croplands and settlements exist more than 50 km far from glaciers that is below EL 2100 m in



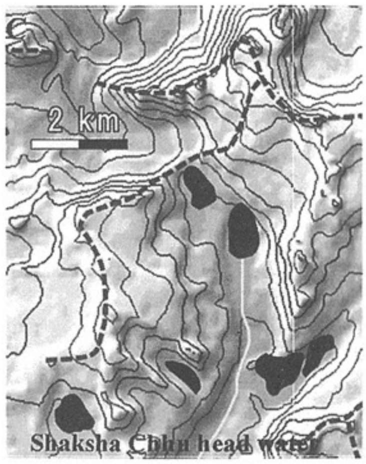


Fig.2 Mangde Chhu and its surrounding topography.
A: Watershed of Mangde Chhu, the area is solid-line frame in figure 1. Dashed frame gives the location of B and C. ASTER DSM with the Read Relief Image Map(c) by Tatsuro Chiba (Asia Airsurvey Co. LTD). **B** and **C**: Pilot site of Glacial lakes in this study.

Table 1 GLOF events in the Bhutan Himalaya

Date	Source of flood	Basin	Cause of outburst	Remarks
mid 20th cent.	Chgarung Glacier	Kuri Chhu western headwater	unknown	Satellite image shows devastated valley[8].
1957	Tarina 1 glacial lake	Pho Chhu western headwater	Glacier ice avalanche	1)
1960	unknown	Pho Chhu headwater	unknown	Flood continued 5 days at Punakha[1), 2)]
7th Oct. 1994	Luggye Tsho	Pho Chhu eastern headwater	moraine dam or right bank collapse or water inflow from glacier	7)
29th April 2009	Tshojo Glacier	Pho Chhu eastern headwater	unknown	

riverbed elevation. In the middle stream, most of them have been developed on the gentle slopes rather than valley floor, because valley is narrow and steep. Meanwhile, partial open valleys allow land use at EL. 500~600 m, 1000 m, 1900 m, 2000~2100 m in river bed elevation.

3. GLOF EVENTS AND MITIGATION WORKS IN BHUTAN

(1) GLOF events in Bhutan

Table 1 shows the past cases of GLOF in Bhutan. In 1994, a GLOF from Luggye Tsho occurred along Pho Chhu. Punakha Dzong (Bhutanese traditional building of local government and religious institutions) was isolated and damaged with 21 casualties[7)].

On 29th April 2009, Lunana, eastern Pho Chhu, a muddy flood occurred from Tshojo Glacier which is one of the biggest debris covered-type glacier in Bhutan. Water level rose by 2 meter around Punakha, 75 km of lower reach from the source. Such a disturbance of local residents due to GLOF was the first time after 1994 event.

On the other hand, previous studies based on satellite and geological data suggest possibilities of GLOF occurrence in Bhutan. CORONA satellite imagery in 1967 shows devastated valley with fresh sediment in Kuri Chhu headwater in the northern side of the Himalayan range. It means that debris and/or mudflow event must have occurred in the valley not so long ago[8)].

Furthermore, there is a massive thick sand layer in river terrace sediment at 1.5 km north from Punakha Dzong. In comparison with huge volume of the sand which is sediment of the 1994 GLOF, it can be attributed to the massive thick sand layer was formed by a GLOF event in the ancient time[9)].

(2) GLOF mitigation works in Bhutan

In response to the GLOF event in 1994, excavation works on the moraine for water level lowering of Raphstreng Tsho was carried from 1996 to1998[2)]. Similar excavation work in Thorthormi Tsho, which is located between Luggye Tsho and Raphstreng Tsho, also has been performed from 2009 to 2012. Additionally, Department of Energy has installed early warning system for GLOF and flash flood in the lower stream from 2010. However, these mitigation works have not conducted in other basins in Bhutan.

4. EXPECTED GLOF HAZARDS IN MANGDE CHHU WATERSHED

(1) Risk factor in and around the lakes

a) Surrounding topography

On 11th April 2010, a GLOF occurred at Hualcan glacier, in the Cordillera Blanca, Peru. The flood was caused by crossover of a big wave due to an ice avalanche falling from 1000 m in height. According to such past events in the Himalaya and Peru, most of GLOFs were induced by ice avalanche from glacier collapses[10)]. In the Mangde Chhu basin, glacier ice which seems to be dangerous situation is located on the left bank of Metatshota Tsho, western upper branch. On the other hand, based on the tentative study based on gradient of lower slope of the moraine dam that 8 lakes should be further surveyed in the field.

b) Bathymetric topography

We conducted field survey at four glacial lakes among the above-mentioned potentially dangerous lakes. Metatshota Tsho shows wide and thick moraine and thin bathymetric profile that seems to be stable condition. Thus, a catastrophic outburst flood from the ice avalanche in Metatshota Tsho hardly occurs. Meanwhile, two lakes in Shaksha Chhu headwater (northwestern branch of Mangde Chhu) dammed up by the thin moraine. Further investigation such as electrical exploration for finding dead ice on the moraine is required.

(2) Hazard assessment for the failure of a moraine dam

Overtopping of a dam, failure of dam slopes, piping into a dam, settlement of a dam body and other phenomena with the melting of the inside ice body including them are pointed out as the provoking causes of the failure of moraine dam which is the trigger of GLOF. Among these, the overtopping of a dam is considered to be the main cause.

Table 2 Material Properties of the moraine

	Bhutan		Nepal		
	Lake A	Lake D	Imja No.1	Imja No.2	Imja No.3
Specific Gravity of Soil Particles	2.635g/cm³	2.641 g/cm³	2.660 g/cm³		
Bulk Density (Dry)	1.723g/cm³	1.336g/cm³	1.689g/cm³ (1.258~2.121g/cm³ : 70% reliability)		
Void Ratio	0.53	0.98	0.58 (0.254~1.115 : 70% reliability)		
Porosity	34.60%	49.40%	36.50% (20.3~52.7% : 70% reliability)		
D_{10}	0.002mm	0.01mm	0.27mm	0.037mm	0.037mm
D_{30}	0.19mm	0.54mm	1.2mm	0.76mm	0.50mm
D_{60}	1.4mm	1.8mm	3.3mm	4.0mm	4.0mm
Uc	700	183	12.2	108.12	108.12
Uc'	12.9	15.9	1.48	3.9	1.69
Clay	14%	9%	5%	5%	6%
Silt	6%	2%	3%	9%	9%
Sand	52%	51%	50%	43%	40%
Gravel	28%	38%	42%	43%	45%
Cohesion	-	-	0kN/m²		
Internal Friction Angle	-	-	35.6 degrees		

However, they do not result in the occurrence of a flood. In other words, the slide and settlement are the trigger of increasing quantity of the outflow. In addition, even if the quantity of outflow increases, the dam body is eroded slowly without rapid drainage of the lake water, and as a result, the glacial lake may disappear. Therefore the authors have thought that the risk assessment for GLOF is useful from this point. Simulation of overtopping was carried out and the outburst risk which was evaluated from the hydrograph.

The BREACH model[11] was used by this analysis. In the analysis, the geometry data such as the cross-section of the dam were fixed, and the testing results of soils sampled at the glacial lake in Bhutan and Nepal (Table 2) were used as material properties. The quantity of the lake water and the inflow had been changed step by step, and consequently hydrographs were simulated under each condition. As an example of the results, Fig.3 shows the changes of peak discharge and the outflow duration time of the hydrograph with the change of inflow. When the inflow is not so large, the peak discharge shows a little peak in the early stage, and the outflow is continued for long time without increasing rapidly. On the other hand, when the inflow become large, the big peak discharge is showed in the early stage and the outflow is over in a short time. As for the type of the latter, it is thought that the outburst of GLOF is equivalent to this, and it is thought that this simulation evaluates

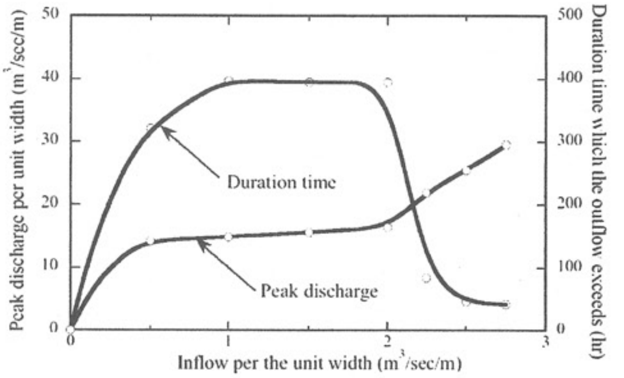


Fig.3 Relationship between the change of the peak discharge and the duration time of outflow with the change of the inflow (by BREACH Model analysis)

the degree of risk about not only the collapse of the dam but also the developing of outburst.

As above, the outburst is evaluated by using the hydrograph based on the results of the simulations about overtopping of a moraine. In this case, the necessary data are the geometry and the material properties of the moraine dam, and the water balance data of the glacial lake such as the volume of the lake water and the inflow from the upstream. When it is considered that the glacial lakes have been a high mountains area more than altitude 4,000 m, it is difficult to get these data. Therefore, it is recommended that we suppose the average value of the glacial lake based on findings performed about some glacial lakes and then quantitative evaluation is enabled.

5. GLOF INDUCED HAZARD AROUND MANGDE CHHU BASIN

(1) GLOF Risk at Mangde Chhu River Basin

The 1994 GLOF by Luggye lake breach in Punatsan Chhu river basin, which took toll up 21

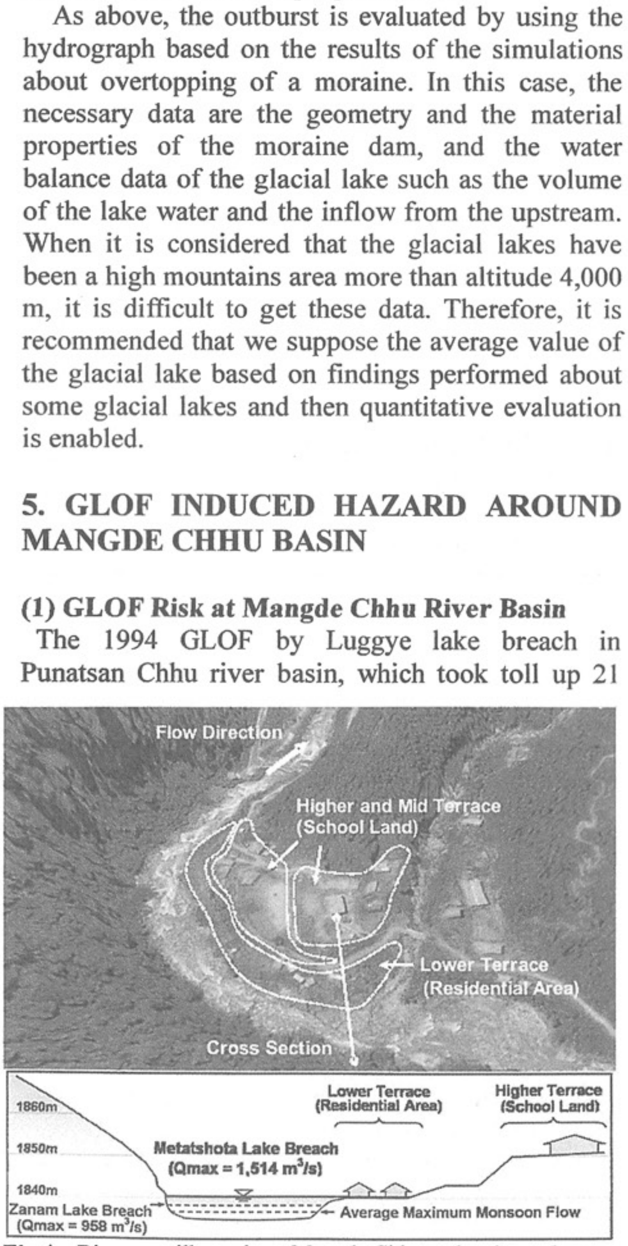


Fig.4 Bjeezam village along Mangde Chhu and estimated water level uprising by GLOF from Zanam and Metatsota lake

deaths, was estimated 20 M m^3 in flood volume and 2,500 m^3/s in peak discharge at Punakha, 95 km downstream of Luggye lake[12]. The water level uprising was recorded plus 4.5 m at Wondue-Phodrang hydro-station. In Mangde Chhu river basin, however, no glacial lake comparable size to Luggye lake has been confirmed based on bathymetric survey at the moment.

In this study, we have simulated the arrival peak discharge of GLOF from two lakes in Mangde Chhu river basin, Zanam lake and Metashota lake, whose breach flood volumes are assumed 6 M m^3 and 16 M m^3 respectively (Fig. 4). Consequently, in case of worst scenario of GLOF from Metatshota lake, the peak discharge was estimated 1,500 m^3/s at Bjeezam, 70 km downstream of the lake, and the several houses on the lower terrace plain are presumed to be washed away by flood (Fig. 4).

On the other hand, temporally natural dam along V-shaped river channel is one of the considerable factors to assess the GLOF damage at the lower stream. During hurricane Aila on May 2009, a huge amount of debris more than 50,000 m^3 from a tributary was damming up the main channel of Mangde Chhu River. Furthermore, it was reported that the 1994 Luggye GLOF has formed temporally dam at the bottleneck, 17 km downstream of the lake[13]. GLOF may destroy such temporally natural dam and wash down involving the huge amount of debris and sediments to the downstream.

Large amount of Woody debris supplied by riverbank erosion is also an important risk factor of GLOF. National highway supporting the physical distribution of mountainous country of Bhutan is across Mangde Chhu at Bjeezam and Tingtibi. Once woody debris is stacked and wash out the crossing bridge beans, the highway will be blocked over a long duration and it will cause a serious economic damage at regional and national level.

(2) Landslides and bank erosion due to GLOF

Detection of landslide slopes is essential for hazard assessment of GLOF along the river, because the occurrence of GLOF may reactivate potential landslides by riverbank erosion. In this paper, we introduce landslide distribution (Fig. 5) in the middle basin of EL. 1,200 m, based on interpreted satellite images and results of field survey. The 13 large-scale landslide bodies (A to M) are recognized from a character of topography (Fig. 5-A). The landslide body A formed by deep-seated landslides has over 4 km in length and 3 km in width. In addition, there is a linear-depression, 2km in length on the east outside of landslide body B. It is thought that rock creep formed this linear depression. In field survey, we detected many secondary landslide

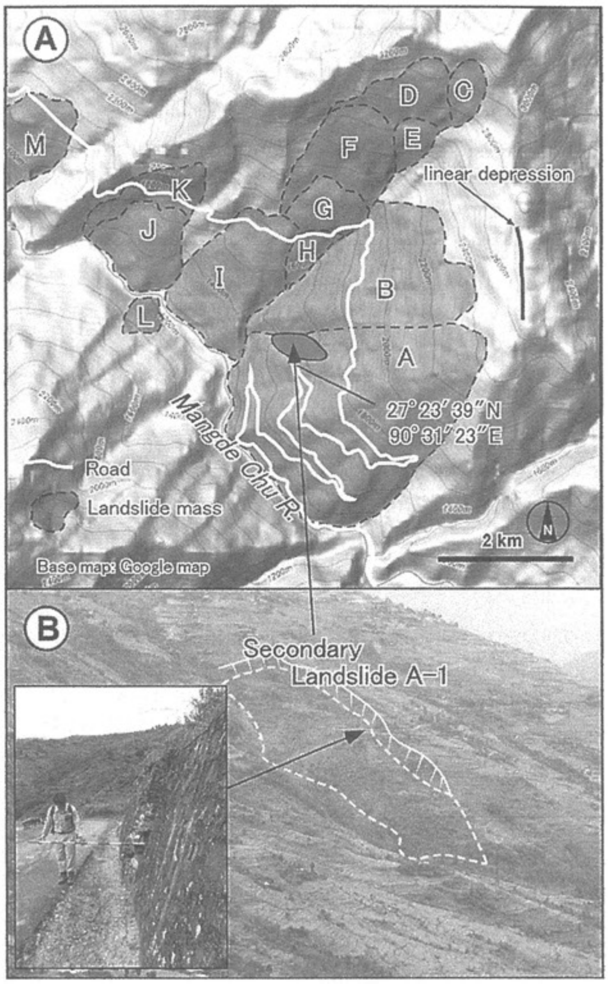


Fig.5 Large-scale landslide distribution (A) and secondary landslide (B)

mass in the large-scale landslide body. For example, the retaining wall on the boundary of the landslide body A-1 (Fig. 5-B) has displaced by recent landslide activity. It is thought that landslide is the main slope development possess as observed above along Mangde Chhu.

Riverbank erosion due to GLOF often induces landslides on the slopes of unconsolidated materials such as talus and fluvial and glacial deposits in narrow valleys. Continuous bank erosion which originated from the GLOF from Nare Glacier in 1977 have been producing huge sediments to downstream in eastern Nepal, because the valley side slopes consist of moraines formed by past glaciations. During the GLOF from Luggye Tsho lake in 1994, the river terraces occupied by paddy fields and a bridge were washed away due to the erosion of composing sandy deposits along Pho Chhu[6].

Susceptibility of bank erosion by GLOF can be evaluated through the comparison of tractive force of GLOF and sizes of bank materials. Grain size analysis will be required at the erosion-prone sites along the Mangde Chhu.

(3) Risk areas around Trongsa

Trongsa town area has the maximum density of population and households among its district.

Therefore this area is highly vulnerable during natural calamities like GLOF. It has a total population of 2,695 and 528 households. Trongsa town is situated over a steep terrain and Mangde Chhu cuts through the bottom of the steep Trongsa valley. It also has lots of past/old landslide scars. In the event of a GLOF in Mangde Chhu, there are chances of landslide reactivation in this region.

(4) Risk areas around Langthel, Trongsa

Langthel village is about 50 km away from Trongsa town, towards the south. It has a population of 2637 and 556 households. The fact that Langthel lies at a lower elevation than Trongsa town has higher chances of getting affected by Mangde Chhu in the event of a GLOF. Therefore proper geological studies have to be done in this area.

6. Conclusion –necessary future work for GLOF hazard-

Comprehensive GLOF risk assessment is vital issue in Bhutan Himalaya. SATREPS (Science and Technology Research Partnership for Sustainable Development) project, which has been launched under JICA and JST since 2009, aims to assess GLOF risk from viewpoint of flood damage and sediment disaster risk in the Mangde Chhu river basin.

According to geomorphological and bathymetric researches in this project, several high-risk glacial lakes including Metatshota Lake, which was estimated as a hydrological potential lake to damage residential area in the downstream, has been extracted in the Mangde Chhu river-basin. Detail breach modeling based on geo-technical approach and flood hazard zoning are ongoing. On the other hand, unstable slopes and landslides have been figured out by satellite image analysis and field surveys. Reactivation of such unstable slope by riverbank erosion of GLOF may cause serious damages to not only the area along the river but also those of higher elevation where houses and national highway are located.

GLOF is a "multiple hazard" including flood, river-channel block and landslide, which are in close relation with geomorphological and geological predispositions, hydrological and meteorological factors, and climate changes as well. For the mitigation of GLOF hazard in regional and national level, the comprehensive watershed management and enhancement of disaster management in consideration of geomorphology and geology are the important issues.

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