Glacial Lakes and Their Outburst Flood Assessment in the Bhutan Himalaya

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Abstract

GLOF (glacial lake outburst flood) events are common phenomena in the high mountain areas of the Bhutan Himalaya in the past 50 years, and have been accelerated in the recent years. Field observations and investigation by map and satellite images indicate that most supraglacial lakes tend to connect each other and grow up to a large lake rapidly, and that moraine-dammed lakes were formed and rapidly expanded after the 1970s due to retreating and/or melting of glaciers. Assessment on occurrence of triggers, impact to the lakes, and vulnerability of moraine-dams suggests that there are at least 5 potential dangerous glacial lakes in the northwestern and northern Bhutan. Dangerous glacial lakes are Lugge Tsho, Raphsthreng Tsho, and Thorthomi Tsho in eastern Lunana. Since these three glacial lakes still contain a large volume of water, and are bounded each other and interact sensitively through water flux and erosion. Two Tarina Lakes are also dangerous due to occurrence of the ice falling from glacier termini. Constant and regular monitoring of glaciers and glacial lakes are urgently required to prepare necessary mitigation activities.

Key words: Bhutan Himalaya, glacial lake outburst flood, GLOF, moraine-dammed lake, risk assessment

1. Introduction

Global climatic change during the latter half of the twentieth century has affected a significant impact on the high mountainous glacial environments. Glaciers in the Himalayas are shrinking more rapidly than glaciers in the other regions of the world under the influence of the recent global warming (e.g. Kadota *et al.*, 1997). It is conceivable that glaciers in Bhutan are so sensitive to the global warming that they are under strong influence of the summer monsoon, and most of the glaciers have retreated rapidly in these 35 years (Karma, 2001)

The rapid retreat and/or melting of large glaciers form a large number of proglacial lakes and/or supraglacial lakes. Most of the proglacial lakes are typical moraine-dammed lakes that are formed between glacial terminus and frontal moraines. Due to an increase in rates of the snow and ice melting, large amount of water accumulates in these lakes. Sudden discharge of large volumes of water from the lakes mainly by the moraine-dam failure causes glacial lake outburst floods (GLOFs) in valleys downstream. The GLOFs result in serious death tolls and destruction of valuable natural resources in the Himalayas (Richardson and Reynolds, 2000a, b; Mool, 2001). The Himalayan regions including the Bhutan Himalaya have suffered many GLOF events (Ives, 1986; Mool, 2001). GLOFs from the Bhutan Himalaya were recorded at least in the early 1940s, 1957(?), 1960, 1969, and 1994 (Gansser, 1970; Geological Survey of Bhutan, 1999: 2). The 1994 GLOF was triggered by partial breaching of Lugge Tsho Glacial Lake, and killed over 20 persons (Watanabe and Rothacher, 1996; Geological Survey of Bhutan, 1999: 2).

Monitoring of the change of glaciers, glacial lakes, and the surrounding environments is urgent need for the accurate assessment on the future risk potential in the Bhutan Himalaya (Wangda, 2000). A Bhutan-Japan Joint Research started in 1998 for the following objectives, which are useful for the future monitoring on the variations of glacial lakes: (1) Preparation of the updated inventory of major glacial lakes located in

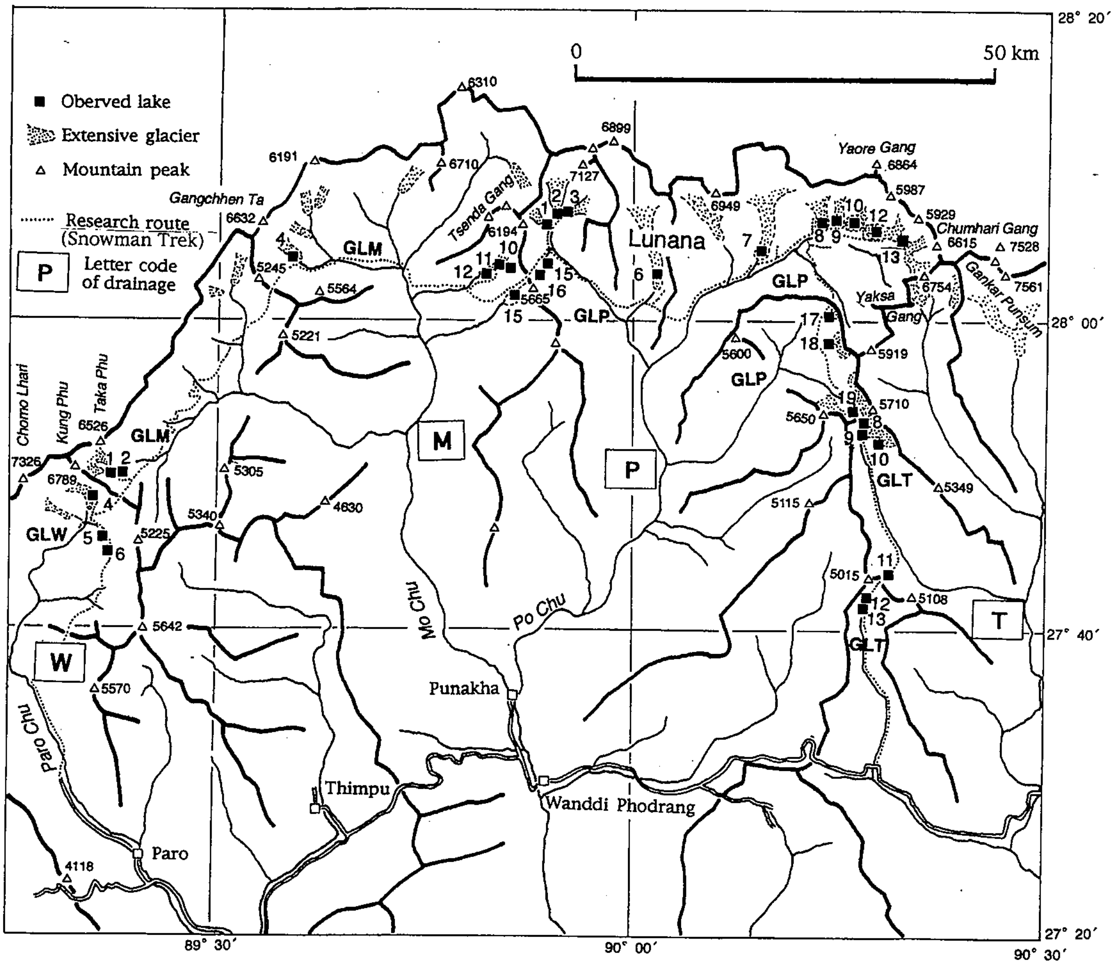

Fig. 1 Research route, river basins, and glacial lakes in the Bhutan Himalaya.

the Bhutan Himalaya; and (2) Assessment on the danger of GLOF including ranking of vulnerability of glacial lakes by combined study on the variations of glacial lakes and the surrounding glacier area. The results of the research were reported as an unpublished document (Ageta and Iwata, 1999).

In this report, we indicate risks of GLOFs of some glacial lakes in the Bhutan Himalaya, and propose possible measures for avoiding risks of GLOFs on the basis of this research and available information.

2. Methods of Study

2.1 Field observation

The field observation was carried out along the route of "Snowman Trek" in the northwestern and northern parts of Bhutan in September and October, 1998. Figure 1 shows the research route and glacial lakes that were studied. Glaciers, glacial lakes, and landforms were mapped in the field aided by satellite imagery (SPOT-XS: taken in Dec. 1993; enlarged prints at a scale of 1:50,000), and topographic maps at the same scale (1:50,000) compiled by Survey of India in the 1960s by aerial photographs taken between 1956 and 1958. Large glacial lakes concentrate in the Lunana area, northern Bhutan, especially in the Thanza area. Large moraine-dammed glacial lakes and glaciers with supraglacial lakes exist in a narrow area and show complex landscapes (Fig. 2).

2.2 List up of glacial lakes

Geological Survey of Bhutan (1999) published an inventory of glaciers and glacial lakes in the headwaters of the major river basins of Bhutan. Code numbers and letters of the glaciers, glacial lakes, and drainage basins in this report are adopted following those appeared in the inventory. Code letters of the first-order river basins such as M and P, and numbers of glacial lakes are shown in Fig. 1. Letter codes G and GL designate the glacier and glacial lake, respectively. For example, Glacier No. 10 and Glacial Lake No. 10 located in the drainage basin P are labeled as GP 10 and GLP 10, respectively. Geographical names such as villages, rivers, mountains, and so on are also followed the published inventory. Information on glacial lakes was given based on our own field observation and was complemented by various documents such as satellite images, maps, literatures, and unpublished photographs. Particularly, Glacial Lake Inventory Maps by Geological Survey of Bhutan (1999) (1:50,000 in scale) and sketch maps drawn by Gansser in 1967 (Gansser, 1970) provided useful information.

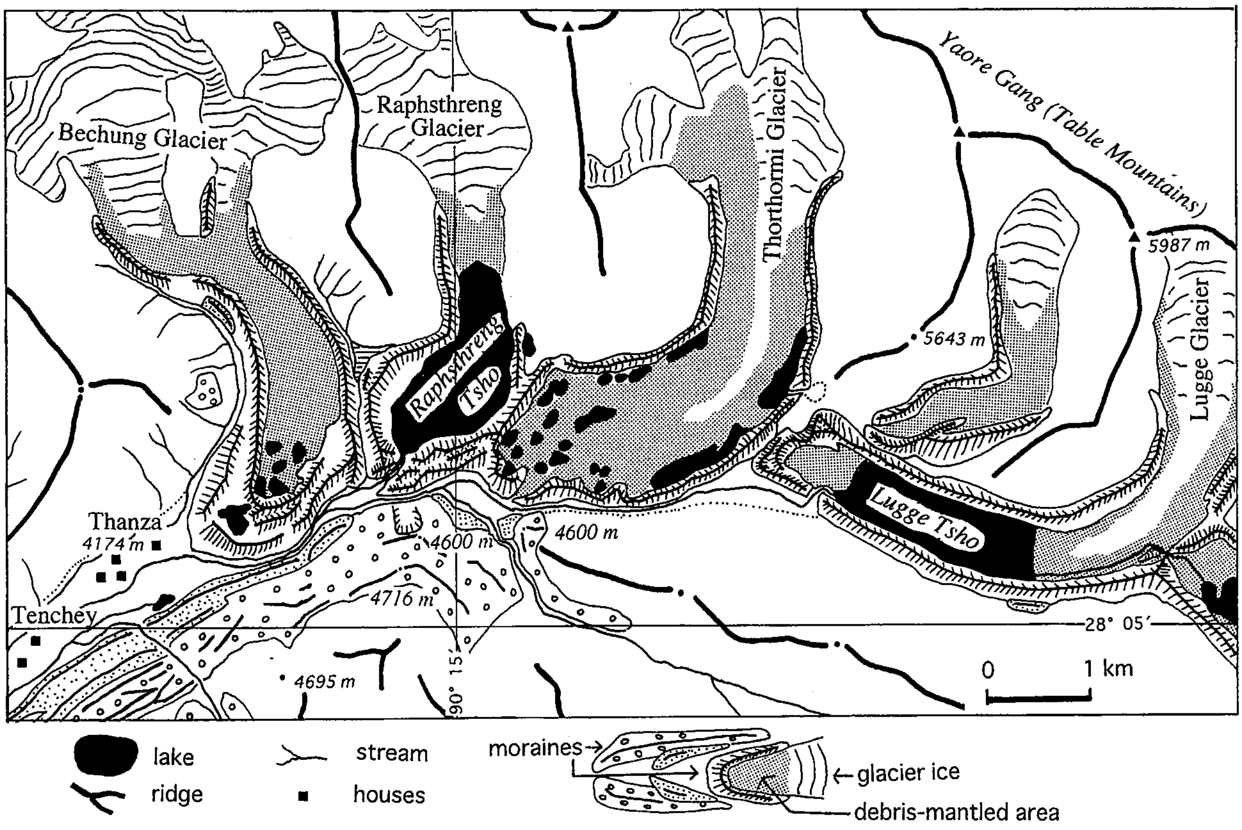

Fig. 2 Glaciers, glacial lakes, and moraine dams in Thanza area, eastern Lunana, northern Bhutan.

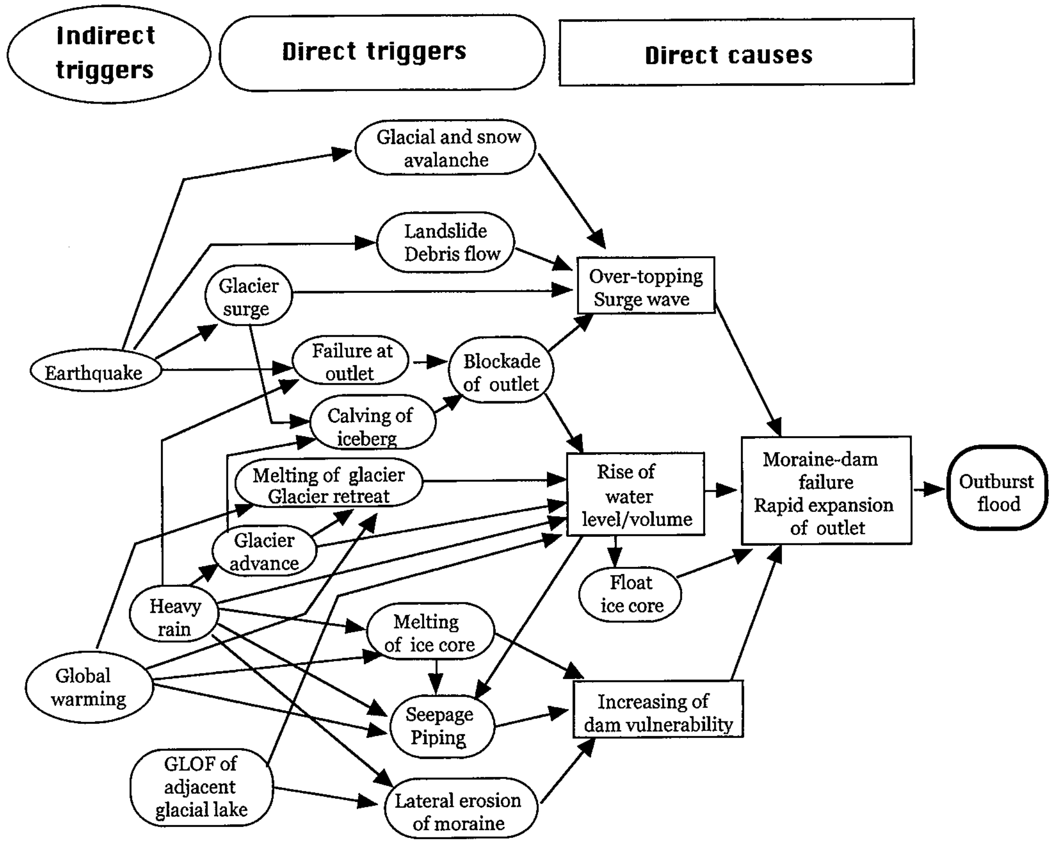

Fig. 3 Cause and effect relationships among possible triggers and causes for GLOF of moraine-dammed lakes in the Bhutan Himalaya.

2.3 GLOF risk assessment

Risk assessment of GLOF can only be made by careful evaluation of numerous factors regarding both outburst potential of glacial lakes and downstream impact, but in this report we focused only the outburst potential of glacial lakes. Outburst potential (future outburst possibility of lakes) can be predicted by (1) understanding of future occurrence of lake outbursts and (2) future changes of related phenomena that influence and impact the glacial lakes. There are considerable reports on past GLOFs in the Himalayas (Gansser, 1970, 1983; Ives, 1986; Vuichard and Zimmermann, 1987; Watanabe and Rothacher, 1996; Yamada, 1998, 2000; Geological Survey of Bhutan, 1999; Richardson and Reynolds, 2000a, 2000b; Mool, 2001).

Consulting these reports, triggers and causes of lake outburst were examined for cases in the Bhutan Himalaya. Figure 3 shows possible triggers and causes for GLOF of moraine-dammed lakes in the case of the Himalayan Mountains. We distinguish direct causes from triggers or impacts of GLOF. Triggers or impacts change the lake water and moraine-dam conditions, and then induce moraine-dam failure and/or sudden expansion of outlet channels. Complicated cause-effect relationships exist among factors of direct and indirect triggers, and direct causes.

Based on this schematic diagram of the cause-effect relationships, items of assessment of GLOFs are listed in Table 1 and a check sheet for risk assessment of moraine-dam failure and/or lake burst in the Bhutan Himalaya was prepared (Fig. 4). The contents of the check sheets cover GLOF history, glacial lake, related glacier, glacier front/lake interface, glacial lake/moraine-dam interface, and moraine-dam. Items and headings were examined, checked, and filled based on the field observations and other documents and information mentioned above. In conclusion overall assessment is proposed: (1) probability of moraine-dam failure and its direct cause and triggers; and (2) degree of danger. The degree of danger is a probability of hazard in the downstream area which largely depends on the water volume of the lake, geomorphological features in the down reaches, and status of infrastructures and habitations in the downstream area, although we were not able to enough discuss on environmental and human environments in the downstream areas.

Table 1 A checklist for risk assessment of GLOFs due to failures of moraine-dams in the Bhutan Himalaya.

Record of past GLOFs	Information from inhabitants Historical and observational documents Geological and geomorphological records Geological and geomorphological evidences of the past GLOFs in downstream areas
Glacier and glacial lake basin	Occurrence of glacier avalanches which affect on the glacial lake Occurrence of snow avalanches which affect on the glacial lake Occurrence of landslides and/or debris flows which affect on the glacial lake Occurrence of the glacier surge
Glacier-lake interfaces	Situation of contact between the glacier front and the lake water Activity and fluctuation of the glacier terminus Calving of icebergs and/or ice blocks Supply of glacial debris from the glacier front to the lake
Glacial lake	Area and depth of the lake Shape of the lake basin Rate of lake expansion Condition of supraglacial ponds
Glacial lake-moraine interface	Relative depth at the base of moraine dam Ratio of income and out-flow water volume
Moraine-dam	Volume and shape Geomorphic evolution of inner slopes Component of materials Existence of ice cores Occurrence of seepage and/or piping Age and history of construction Relative height and inclination from the outer base to moraine ridges Geomorphic evolution of outer slopes Relative height and inclination of the outlet channel Shape of the outlet channel Conditions of side slopes of the outlet channel

Data sheet of glacier lake inventory in the Bhutan Himalayas

Code number of glacier lake: ________
Name of glacier lake:
River basin-1st order: ________
-2nd order: ________
-3rd order: ________
Location-Longitude: ________
-Latitude: ________
-Approx.: ________
Dimension-length and width: ________
-depth: ________
-lake surface elevation: ________
Plan shape: ________
Related glacier-name: ________
-type: ________
-interface with lake: ________
Type of glacier lake: ________
Record of past GLOFs: ________
Remarks: ________

Data sources-map: ________
-satellite image: ________
-literature: ________
-field observation: ________

Fig. 4 Format of the data sheet of the glacial lake inventory.

3. Results

Information of glacial lakes and their environments resulted from mapping of glaciers, glacial lakes, and landforms in the field, and obtained from other data sources was compiled in a glacial lake inventory. Risk assessments of GLOFs for these glacial lakes were described on check sheets of the glacial lakes. These results were submitted to Department of Geology and Mines in Bhutanese Government as an unpublished report (Ageta and Iwata, 1999). The following sections, we present the most important part of the results on expansion of glacial lakes, triggers and impact for outburst, and direct causes of moraine-dam failures.

3.1 Expansion of glacial lakes

Results of observation for 30 glacial lakes are summarized in Table 2. These glacial lakes observed are classified into three types based on locations and origins as follows: (1) supraglacial ice-melt lakes or ponds, (2) moraine dammed lakes, and (3) lakes located in basins without glaciers. No glacier-dammed lake was found along the observation route. Distal lakes mean lakes located far from glacier terminus. Lakes in basins without glaciers are located in cirques and glacial troughs scoured by Pleistocene glaciers. Most of supraglacial ice-melt lakes or ponds and moraine-dammed lakes have expanded in recent decades as already reported (Ageta *et al.*, 2000). Here, we show some typical examples.

(1) Supraglacial lakes

Comparisons of toposheets, photographs, and satellite images in different years indicate that most glacial lakes started from small supraglacial ponds and lakes. They expanded and connected each other and grew up to a large lake. Expansion of Thorthomi Tsho (GLP 10), supraglacial ice-melt lakes on Thorthomi Glacier, has been accelerated in the 1990s as shown in Fig. 5. The thin debris-cover on the glacier surface accelerates ice melting and the very gentle gradient of the snout may lead to form a large lake in near future.

(2) Moraine-dammed lakes

Moraine-dammed lakes are entirely or partly surrounded by laterofrontal moraines and are located at ice-marginal, proximal, and distal positions in front of glaciers. They are also formed outside of lateral moraines between the marginal moraines, and moraine ridges of different glaciers and valley slopes.

Tarina Lakes (Tarina Tsho GLP 1 and Mouzom Tsho GLP 2), introduced by Gansser (1970) with a beautiful photograph taken in autumn of 1967, already existed in the 1950s (Fig. 6). The lakes show no large change, but the area of the upper lake (GLP 2) extended upstream remarkably (0.7 km from 1967 to 1988), in comparison with the Gansser's photograph. The size and plan shape of the lower lake (GLP 1) became smaller from 1967 to 1989-90. The cause of the shrinkage is not clear: there are possibilities such as an error of mapping by DGM and increased water drainage by change of the outlet channel form.

Table 2 Glacial lake inventory in the Bhutan Himalaya.

Code No. of glacial lake	Name of glacial lake	Location		Location to glacier	Cause of lake	Occurrence of avalanche	Moraine-dam		
		Longitude °E	Latitude °N				Mass movement[1)]	Relative height[2)]	Outlet channel[3)]
GLW 4		89°21.5'	27°49'	3	3	2	-	3	2
GLW 5	Tsho Phu	89° 22.5'	27° 45.5'	5	4	-	-	-	-
GLW 6		89° 22.5'	27° 45.5'	5	4	-	-	-	-
GLM 1	Chhokam	89° 22'	27° 50.3'	3	3	3	3	2	1
GLM 2	Chhokam	89° 24'	27° 50.7'	4	3	2	3	3	2
GLM 4	Shinchhe	89° 35'	28° 04'	3	3	2	3	-	-
GLM 10	Rodu Tsho III	89° 51'	28° 04'	3	3	5	5	1	1
GLM 11	Rodu Tsho I	89° 50.2'	28° 03.5'	1	1	3	-	-	-
GLM 12	Rodu Tsho II	89° 49.5'	28° 03.2'	3	3	3	3	2	4
GLM 15		89° 52'	28° 01.5'	3	3	2	5	4	5
GLP 1	Tarina	89° 54'	28° 06'	3	3	1	2	3	4
GLP 2	Tarina (Mouzom)	89° 54.5'	28° 06.5'	3	3	2	1	3	4
GLP 3		89° 55.2'	28° 07'	3	3	5	5	4	5
GLP 6		90° 02'	28° 03'	1	1	2	-	-	-
GLP 7		90° 09.8'	28° 04.5'	1	1	5	-	-	-
GLP 8	Bechung	90° 14'	28° 06'	2	1	1	3	3	3
GLP 9	Raphsthreng	90° 15'	28° 06.5'	2	3	1	1	2	4
GLP 10	Thorthomi	90° 16.5'	28° 06'	1	1	1	1	3	1
GLP 12	Lugge	90° 18'	28° 06'	2	3	1	1	3	1
GLP 15		89° 58.2'	28° 04'	3	3	3	4	1	1
GLP 16		89° 58'	28° 03.7'	3	3	3	4	3	4
GLP 17		90° 14.4'	28° 00.2'	3	3	4	3	4	4
GLP 18		90° 14.5'	27° 59'	3	3	4	3	3	4
GLP 19		90° 16'	27° 55.2'	2	3	4	3	3	4
GLT 8		90° 17'	27° 54.8'	2	3	3	5	4	5
GLT 9		90° 17'	27° 54.5'	2	3	3	3	3	4
GLT 10		90° 17.5'	27° 53.5'	2	3	2	3	3	4
GLT 11	Thampe	90° 19.5'	27° 44.2'	5	4	-	-	-	-
GLT 12	Um Tsho Upper	90° 17.5'	26° 43'	5	4	-	-	-	-
GLT 13	Um Tsho Lower	90° 17.4'	26° 40'	5	4	-	-	-	-

Code number of glacial lake are indicated in Fig. 1. **Location to glacier**: 1. Supra-, en-, and sub-glacial; 2. Ice-marginal; 3. Proximal; 4. Distal; 5. In the basin without glacier. **Cause of lake**: 1. By ice melting; 2. Dammed by glacier; 3. Dammed by moraine; 4. Dammed by other landforms; 5. River lake (by poor drainage). **Occurrence of** (glacier/snow) **avalanches**: 1. Extremely high; 2. High; 3. Low; 4. Extremely low or no; 5. Unknown. **1)** Occurrence of mass movement on inner slopes: 1. Extremely high; 2. High; 3. Low; 4. No; 5. Unknown. **2)** Relative height or inclination of the outlet channel: 1. Extremely high; 2. High; 3. Low; 4. Unknown. **3)** Shape of the outlet channel: 1. Narrow and sharp; 2. Narrow and gentle; 3.Wide and sharp; 4.Wide and gentle; 5. Unknown.

Raphsthreng Tsho (GLP 9) has rapidly expanded between the 1950s and 1980s, while in the 1990s the lake maintains almost the same state (Fig. 7). This means that the lake expansion attained the maximum stage, suggesting that the glacial retreat no longer contributes the lake expansion because the glacial bed seems to become steep abruptly upstream from the present position and a bare rock-wall appeared at the end of the lake. The dimension of the lake in 1996 was 1.9 km in length and 0.96 km in width, and the maximum depth of 107 m was recorded (Geological Survey of Bhutan, 1999: 26). Water volume of the lake was estimated as 47×10^6 km^3 in 1986 and 67×10^6 km^3 in 1995 (Geological Survey of Bhutan, 1999: 26).

The Lugge Tsho group including Lugge Tsho (GLP 12), Tsopda Tsho, and Drukchung Tsho (GLP 13) is illustrated in Fig. 8. In the 1950s no water-mass was identified both on Lugge and Drukchung glaciers. Drukchung Glacier lies on the east of Lugge Glacier, and coalesces at the southeastern corner of it. According to Gansser's observation in 1967, many glacier-melt ponds were formed on both glacier surface, and he found clear signs of recent bursting of ponds on Drukchung Glacier (Gansser, 1970). From 1967 to 1988 the supraglacial ponds joined together forming two large lakes, Lugge Tsho (GLP 12) and Drukchung Tsho (GLP 13). By satellite-image interpretation, water of Drukchung Tsho had drained through a supraglacial channel into Lugge Tsho, and water of Lugge Tsho flowed out through clear outlet channel formed in the lateral moraine. Since Drukchung Tsho represents the maximum area in 1988, a considerable quantity of water was probably drained and nourished Lugge Tsho. Lugge Tsho had its maximum area in 1993, and shrank after the 1994 outburst, and successively, the western bank of the lake regressed nearly 500 m. After the 1994 outburst Lugge Tsho became 1.2 × 0.50 km in dimension (Geological Survey of Bhutan, 1999), but no maximum depth has known. Tsopda Tsho, occupied in the outer corner between Lugge and Thorthomi glaciers, disappeared between 1967 and 1988 (Fig. 8).

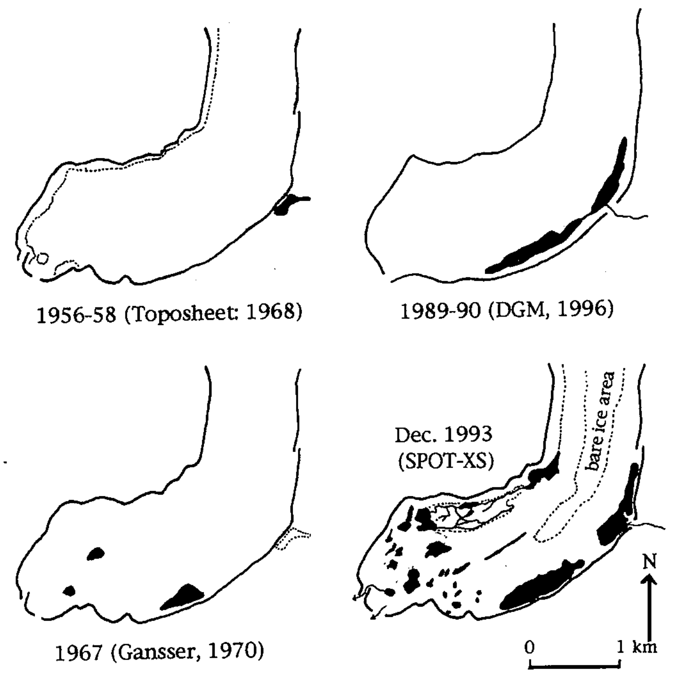

Fig. 5 Expansion of Thorthomi Tsho (GLP 10) (Ageta *et al.*, 2000).

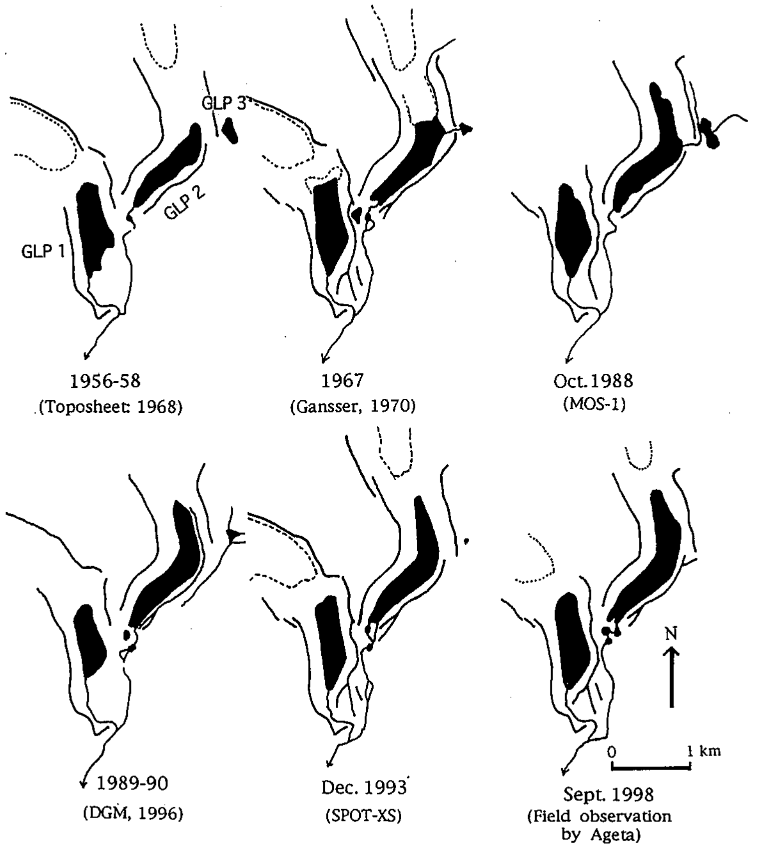

Fig. 6 Change of Tarina Lakes (Tarina Tsho GLP 1 and Mouzom Tsho GLP 2), western Lunana, northern Bhutan (Ageta *et al.*, 2000).

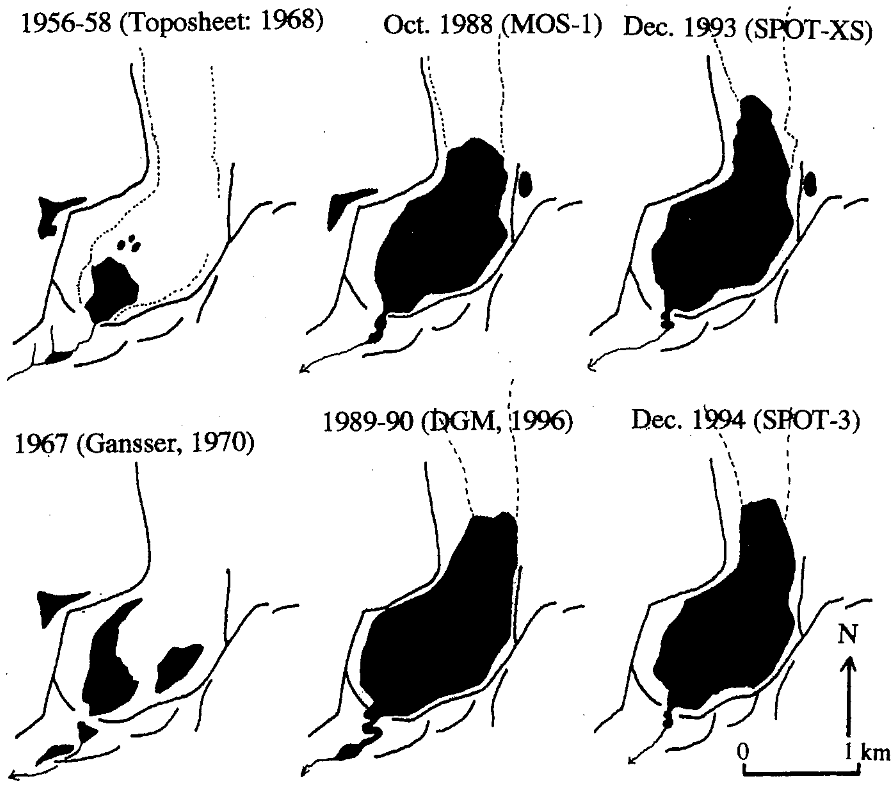

Fig. 7 Expansion of Raphsthreng Tsho (GLP 9) (Ageta *et al.*, 2000).

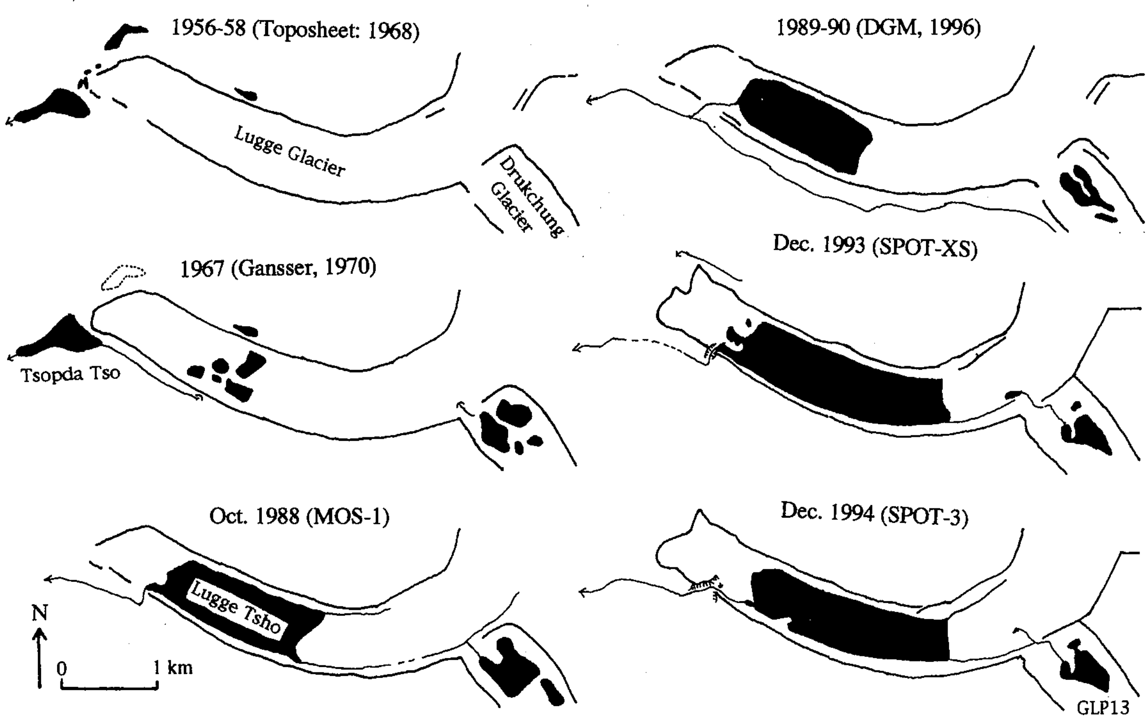

Fig. 8 Expansion of Lugge Tsho (GLP 12), Tsopda Tsho, and Drukchung Tsho (GLP 13) (Ageta *et al.*, 2000).

Rates of the glacial lake expansion are variable with individual lakes. The largest mean annual rate is 160 m year^{-1} of Lugge Tsho between 1988 and 1993. Ageta *et al.* (2000) concluded that the mean annual expansion rates cover in a range of 30-35 m year^{-1}. This value is smaller in Bhutan than Nepal.

3.2 Probable triggers for direct causes

As shown in Fig. 3, there are so many indirect and direct triggers for GLOFs. One of the most important indirect triggers is global warming that causes the rapid lake expansion as mentioned above. In addition, earthquake, due to active tectonic movements of the Himalayas, and heavy rain, driven from summer monsoons and cyclones from the Bay of Bengal, are supposed to be serious indirect triggers, and moreover it is difficult to predict the occurrence. These indirect triggers affect various direct triggers in turn through the complicated cause and effect links as shown in Fig. 3. We refer here only some notable examples of important triggers. On the basis of the previous studies and our investigation, six direct triggers can be pointed out, namely, (1) glacial and snow avalanches, (2) landslides and debris flows, (3) blockade of outlets, (4) seepage and piping in moraines, (5) GLOF or rapid discharge from an adjacent lake, and (6) lateral erosion of moraines.

1) Glacial and snow avalanches

Fall down of hanging ice masses of glacier fronts on the cliffs and/or avalanches from steep walls behind glaciers cause risks of sudden water rising and surge waves. They are the most frequent (over 50%) triggers for past GLOFs in the Himalayas (Richardson and Reynolds, 2000).

Since both the glacial lakes in Tarina (Tarina Tsho GLP 1 and Mouzom Tsho GLP 2) in Lunana are located at the feet of high rock cliffs, water masses of these lakes overflow when the hanging ice masses of glacier fronts GP1 and GP 2 located on the cliffs fall down. Steep glaciers with high and steep backwalls such as Raphsthreng Glacier are very likely to induce impacts of avalanches on glacial lakes. On the other hand, risk of avalanches as a trigger is avoidable for glaciers with gentle and long terminus. At the present state, the glacier front at the eastern margin of Lugge Tsho (GLP 12) is situated so far distance from the steep upstream glacier area that the trigger by avalanche is ineffective (Fig. 2).

2) Landslide and debris flow

Landslide and debris flow occurring in glacial lake basins impact on the lake water and cause surge waves and sudden rise of lake levels. High and unstable inner slopes of the lateral moraines and large taluses of Raphsthreng Tsho (GLP 9) indicate the high probability of landslides which cause considerable high surge waves attacking the dam (Photo 1). Large-scale failures of inner moraine slopes of Lugge Tsho (GLP 12) caused by melting of the ice cores in the moraine lead to the sudden rise of lake water surface.

3) Blockade of the outlet channel

Possible causes of the sudden rise of the Lugge Tsho (GLP 12) lake level are anticipated by blockade of the outlet channel by (a) the failure occurring at around the outlet channel which runs just below the steep inner slope of the lateral moraine, and (b) the obstruction by icebergs calved from the ice cliff at the glacier front (Photo 2).

Photo 1 Raphsthreng Tsho (GLP 9), and erosion on the outer toe of lateral moraine caused by the 1994 GLOF from Lugge Tsho. The excavation made at the outlet. Note traces of fresh rock falls from higher places on the right of the lake, and the altitudinal difference between Raphsthreng Tsho and debris-mantled Thorthormi Glacier.

Photo 2 **Upper:** Lugge Tsho (GLP 12) from the western end. The ice cliff of Lugge Glacier terminus is on the eastern end of the lake.
Lower: Breach in the lateral moraine of Lugge Tsho from outside. It was enlarged leftward on the outburst in 1994.

4) Lake water seepage and piping

We observed that considerable amount of water is leaking from the left-lateral moraine of Thorthomi Tsho (GLP 10) to the river channel from Lugge Tsho. Therefore, the left-lateral moraine is now very unstable condition and very dangerous state for destruction. Since the water levels of supraglacial lakes on Thorthomi Glacier are about 60 m higher than that of Raphsthreng Tsho, it is doubt that the seepage water flows into Raphsthreng Tsho below its water surface (Geological Survey of Bhutan, 1999: 27). Results of water temperature measurements at Raphsthreng Tsho along the moraine between the lake and Thorthomi Glacier indicated no seepage sign due to meltwater from Thorthomi Glacier (Ageta *et al.*, 1999: 31-38).

5) GLOF or rapid drainage from an adjacent lake

Rapid drainage from Drukchung Tsho (GLP 13: 1989-90 in Fig. 8) has probably caused and will cause the sudden rise of the Lugge Tsho (GLP 12) lake level as indicated in Fig. 8. Raphsthreng Tsho is located at lower position than Thorthomi Glacier, and the moraine between them is damming up water flow from meltwater of Thorthomi Glacier (Photo 1). If this moraine-dam will break, water from Thorthomi Glacier and its lakes may involve catastrophic outburst of Raphsthreng Tsho.

6) Lateral erosion to marginal moraines

The left-lateral moraine of Thorthomi Glacier (GP 10), a single slender ridge, is being eroded from both sides. The moraine ridge is getting sharp in form: the inner slope is retreating by the expansion of long fringing lakes along the ridge (Photo 3), and the outer slope is eroding its base by lateral and downward cutting of the river which discharges from Lugge Tsho. The inner slope has retreated rapidly, judging

Photo 3 Marginal lakes and the inner slope of lateral moraine of Thorthormi Glacier.

from the discharge and disappearance of the small pond which existed bounding on the eastern outer slopes of the lateral moraine in 1956-58 (Fig. 5), and its water was discharged from the rupture formed in the lateral moraine.

3.3 Direct causes and moraine-dam vulnerability

In most cases direct causes of outbursts are moraine-dam failure and/or rapid expansion of an outlet channels caused by (1) sudden over-topping of surge waves, (2) gradual rising of water levels, and (3) increasing of dam vulnerability as the results of various direct triggers (Fig. 3). Probability of occurrence of these direct causes depends on moraine-dam configurations such as forms, dimensions, and breaches, and substance of the moraine-dams such as ages, compaction, and ice-cores.

1) Breaches of moraine dams

Many moraine dams have breaches that were formed on occasions of past GLOFs. Some breaches, however, were formed by glacier melt-water erosion before glacial lakes were formed. An important factor for risk assessment is relative height between glacial-lake levels and local base levels. The local base level means a stable datum level which controls erosion locally, and is a relatively flat ground-surface outside the moraine. Configurations of breaches, such as gradients and width of outlet channels, and steepness of sidewalls, are also important factors relating with the characteristics of overflows of lake water. Moraine dams of Tarina Lakes (Tarina Tsho GLP 1 and Mouzom Tsho GLP 2) have breaches as reported by Gansser (1970). Probability of occurrence of the outburst for GLP 2 is considered to be low compared with GLP 1, since the morphological conditions of the outlet channel of GLP 2 are wide and gentle in gradient.

2) Complexity of forms and ages of moraine dams

The moraine dam of Raphsthreng Tsho (GLP 9) is composed of multiple ridges (Fig. 2 and Photo 1). The inner one is morphologically relative fresh and partly covered with unweathered boulders without vegetation, while outer ridges are covered with the dense bush. A buried soil layer was found in between the till layers which constitute the outer ridges. It was dated at around 1900 years BP by AMS radiocarbon methods (Iwata *et al.*, in press, a). These ages imply that the outer moraines are older than the Little Ice Age, and fall into the Holocene. The ages and morphological features with considerable width suggest that the moraine dam itself seems to have strength to keep the lake water. The moraine between Raphsthreng Tsho and Thorthomi Glacier also may be stable at present, because it is composed of the same Holocene moraines. Vulnerability of this moraine will increase, if seepage water from Thorthomi Glacier to Raphsthreng Tsho exists and weakens the moraine as mentioned above.

The left-lateral moraine of Thorthomi Tsho (GLP 10) with simple and sharp ridge is young, probably formed in the Little Ice Age. As mentioned above, this is subjected to severe eroding conditions and occurrence of seepage from glacial lakes. The left-lateral moraine is now very unstable condition and very dangerous state for destruction. Moraine-dam vulnerability is increasing undoubtedly and probability of moraine-dam failure is considered to be high.

3) Melting of ice-cores in moraines

Melting of ice-cores in moraine dams play an important role for increasing of moraine-dam vulnerability. In the Bhutan Himalaya, melting of the ice-core in the moraine was reported to cause the GLOF by the rapid expansion of outlet channel. On October 6-7, 1994, GLOF of Lugge Tsho (GLP 12) killed more than 20 persons and damaged the Punakha Dzong and many houses (Watanabe and Rothacher, 1996; Geological Survey of Bhutan, 1999; Richardson and Raynolds, 2000a, b). The outburst had occurred due to the sudden lateral expansion in a section of the previous small rupture. Because the presence of dead ice was observed in the broken moraine a week after the outburst (Geological Survey of Bhutan, 1999), the moraine failure is thought to have been induced by melting of ice core in the moraine. Clear southward expansion of outlet channel is recognized on the satellite image, SPOT-3 taken just after the GLOF (Fig. 8 and 9).

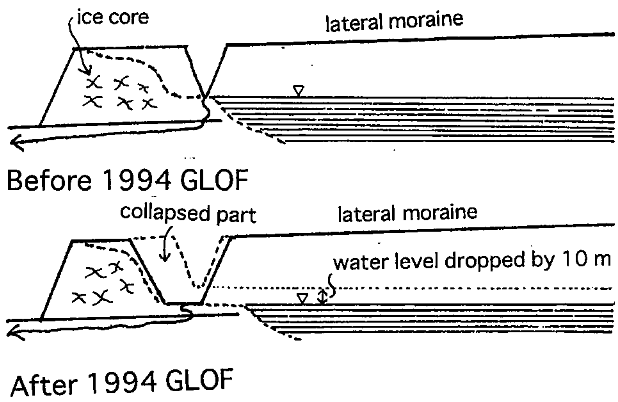

Fig. 9 Schematic diagram of the rupture before and after the 1994 GLOF of Lugge Tsho.

In the wide terminal area at the west of Lugge Tsho, the considerable part of the lake exhibits typical features of glacier karst, which is debris-covered stagnant glacier ice showing chaotic surface-forms with many funnel-shaped holes, hummocks, and ridges shaped by differential ice melting. In the glacier karst area of the west of Lugge Tsho, the debris thickness ranges between 0.5 m to 1.0 m. The ice underneath the debris melts slowly so that it is not likely to induce the rapid lake-level rise.

4. Discussion

4.1 Risk assessment of glacial lakes

As already mentioned, assessment in this research is to make clear the outburst potential (future outburst possibility) of each lake. For this, we understand (1) future occurrence of lake outbursts and (2) future changes of related phenomena that impact the glacial lakes. We predict the following two aspects: (1) probability of moraine-dam failure and its direct cause and triggers, and (2) degree of danger of GLOF in each glacial lake. Results of overall assessment for 30 glacial lakes are summarized in Table 3. Detailed discussion on risk of some notable lakes is given below. Most of other glacial lakes are less dangerous or no dangerous because of their stable moraine dams and/or of their small lake size.

1) Tarina Lakes (Tarina Tsho GLP 1 and Mouzom Tsho GLP 2)

Although the area of the upper lake (Mouzom Tsho; GLP 2) extended upstream remarkably up to 1988, general features of glacial lakes have not changed in comparison with those in a photograph taken in autumn of 1967 by Gansser (1970). Probability of occurrence of outburst for these lakes is considered to be low, since the outlet channels are wide and stable with gentle slope, and since relative height is low between lake levels and local base levels. However, risks remain due to surge waves by fall down of hanging ice masses of glacier fronts on the cliffs.

2) Raphsthreng Tsho (GLP 9)

The lake expansion attains the maximum stage at present and contains large volume of water. The moraine dam is composed of multiple ridges with large dimension and of relatively old age. The features suggest that the moraine dam itself seems to have strength to keep the lake water. However, high and unstable inner slopes of the moraines and large taluses indicate that the lake has high probability of landslides which cause considerable high surge waves attacking the dam. The lake level of Raphsthreng Tsho is fairly lower than that of Thorthomi Glacier. If the moraine between them will break, outburst from Thorthomi Tsho may involve catastrophic outburst of Raphsthreng Tsho. Although this moraine looks like stable at present, vulnerability of this moraine will increase, if seepage water from Thorthomi Glacier to Raphsthreng Tsho exists and erodes this moraine.

3) Thorthomi Tsho (GLP 10)

There is a possibility that the debris cover of Thorthomi Glacier and the very gentle gradient of the snout lead to be a large lake in the near future. The left-lateral moraine is being eroded from both sides and the moraine ridge is getting sharp in form. The both slopes are eroding their bases: by lateral and downward cutting of the river from Lugge Tsho as well as by lateral erosion by the lake. In addition, considerable amount of water is leaking from lakes inside to outside through the moraine. The left-lateral moraine is now very unstable condition and very dangerous state for destruction. Dam vulnerability is increasing undoubtedly and probability of moraine-dam failure is considered to be high.

4) Lugge Tsho group: Lugge Tsho (GLP 12), Tsopda Tsho, and Drukchung Tsho (GLP 13)

Although Lugge Tsho shrank after the 1994 outburst, it contains a large volume of water.

Table 3 Results of risk assessment of moraine-dam failure and/or lake burst in the Bhutan Himalaya.

Code number of glacier lake	Name of glacier lake	Degree of occurrence of moraine-dam failure and/or outburst	Degree of danger (probability of hazard)
GLW4	-	Low probability	Less dangerous
GLW5	Tsho Phu	Medium probability	Less dangerous
GLW6	-	Medium probability	Less dangerous
GLM1	-	Low probability	Less dangerous
GLM2	Chhokam Tsho	Low probability	Less dangerous
GLM4	Shinchhe Tsho	Low probability	Less dangerous
GLM10	Rodu Tsho III	Low probability	Less dangerous
GLM11	Rodu Tsho I	No occurrence	No danger
GLM12	Rodu Tsho II	Low probability	Less dangerous
GLM15	-	Impossible to evaluate	Impossible to evaluate
GLP1	Tarina Tsho	Medium probability	Dangerous
GLP2	Mouzom Tsho	Low probability	Dangerous
GLP3	-	Impossible to evaluate	Impossible to evaluate
GLP6	-	Low probability	Less dangerous
GLP7	-	No occurrence	No danger
GLP8	Bechung Tsho	Low probability	Less dangerous
GLP9	Raphsthreng Tsho	Medium probability	Dangerous
GLP10	Thorthomi Tsho	High probability	Dangerous
GLP12	Lugge Tsho	Medium probability	Very dangerous
GLP15	-	High probability	Less dangerous
GLP16	-	Low probability	No danger
GLP17	-	No occurrence	No danger
GLP18	-	No occurrence	No danger
GLP19	-	Low probability	Less dangerous
GLT8	-	Low probability	No danger
GLT9	-	Low probability	No danger
GLT10	-	Low probability	Less dangerous
GLT11	Thampe Tsho	No occurrence	No danger
GLT12	Um Tsho Upper Lake	No occurrence	No danger
GLT13	Um Tsho Lower Lake	No occurrence	No danger

Accordingly, sudden rise of water level of Lugge Tsho should be monitored regularly. Possible causes of the sudden rise are anticipated as follows: (1) Blockade of the outlet channel by the failure occurring at around the outlet channel which runs just below the steep inner slope of the lateral moraine; (2) Large-scale failure of the inner moraine caused by melting of the ice core in the lateral moraines; (3) The rapid discharge from Drukchung Tsho (GLP 13). Since the Thanza area is located below the lower limit of the permafrost zone (Iwata *et al.*, in press, b), melting of the ice core proceeds in considerable rapid speed. Risk of sudden water rising and surge wave caused by avalanches is quite low. The ice underneath the debris of the frontal moraine melts slowly so that it is not likely to induce the rapid lake-level rise.

4.2 Possible measures for their mitigation and monitoring

In spite of Gansser's warning in the 1960s (Gansser, 1970), any measures except the 1986 Lunana Lake Expedition by Geological Survey of India were not taken against GLOF in the Bhutan Himalaya before the 1994 GLOF from Lugge Tsho. After that GLOF, Geological Survey of Bhutan and some groups carried out field research and assessment on glacial lakes in Lunana. Results of these activities appeared in unpublished reports. They focused the risk of outburst of Raphsthreng Tsho, therefore Government of Bhutan decided to carry out excavation the outlet channel of Raphsthreng Tsho by human power. The excavation started in 1996 and finished in 1998 to widen the outlet and lower the water level by 4 m. This mitigation activity reduced the risk of GLOF, but the lake still contains so huge volume of water that regular monitoring is quite necessary.

As mentioned above, some dangerous glacial lakes were listed by the present investigation (Table 3). Possible measures of mitigation for two attentive glacial lakes are mentioned below as follows:

Glacier melt lakes on the ablation area of Thorthomi Glacier are expanding by the accelerated ice melting, and the vulnerable lateral moraine also increasing by the lake and channel erosions. Monitoring of lakes and moraines, especially leaking water through the moraine, should be carefully carried out. Glacio-hydrometeorological observations such as heat balance, ice melting, and pond evolution on the lower part of Thorthomi Glacier, and geological and geophysical surveys for internal structures of moraines are recommended to provide basic information on the prediction of the lake formation and moraine failure.

There are possibilities that the sudden rise of lake water surface of Lugge Tsho (GLP 12) caused by failures of the inner moraine and blockade of the outlet channel. These failures and blockade may occur by melting of the ice cores in the moraine. Sudden rise of water level of Lugge Tsho should be monitored regularly.

At the same time in the excavation, Geological Survey of Bhutan made an inventory of glacial lakes in the every river basins of Bhutan (Geological Survey of Bhutan, 1999). ICIMOD also made inventory of glacial lakes in the Himalayas (Mool *et al.*, 2000). These inventories show that there are many dangerous glacial lakes in the Bhutan Himalaya besides those indicated in Table 3. Constant and regular monitoring of glaciers and glacial lakes are urgently required to prepare necessary mitigation activities.

5. Conclusions

Observed 30 glacial lakes are classified into three types based on locations and origins as follows: supraglacial ice-melt lakes or ponds, moraine dammed lakes, and lakes located in basins without glaciers. Field observations and investigation by maps and satellite images indicate that most supraglacial ice-melt lakes tend to connect each other and grow up to a large lake rapidly, and some moraine-dammed lakes were formed and rapidly expanded after the 1970s due to retreating and/or melting of glaciers. Formation and expansion of glacial lakes are due to the global warming in the recent decades and the risk of GLOFs is increasing year by year. Six direct triggers of moraine-dam failure and/or outburst can be pointed out: glacial and snow avalanches, landslides and debris flows, blockade of outlets, seepage and piping in moraines, GLOF or rapid discharge from an adjacent lake, and lateral erosion of moraines. Occurrence of these triggers varies in a wide range depending on the characteristics of the lakes themselves, features of moraine-dams, and surrounding landforms and glacial environments. A very dangerous glacial lake is Lugge Tsho (GLP 12), which is still large in water volume and has probability of rapid rise of water level by blockade of outlet or outflow from GLP 13. The moraine dam of GLP 10 (Thorthomi Tsho) has so high probability of occurrence for the failure that this glacial lake needs careful monitoring. Probability of occurrence of moraine-dam failure of Raphsthreng Tsho is mitigated by excavation since 1996, but the risk of hazard is still high and is a dangerous lake, because the lake contains a large volume of water which will has possibility to produce surge waves by falling of ice from the glacier or debris from surrounding moraines and slopes. Since three glaciers (GP 9, 10, 11) and their lakes (GLP 9, 10, 12) are bounded each other and interact sensitively through water flux and erosion, this area is the most vulnerable for GLOF. Monitoring of this area should be continued every year. So-called Tarina Lakes (GLP 1 and 2) are also dangerous because one cannot deny the ice falling from glacier termini. Constant and regular monitoring is mostly important for all glaciers and glacial lakes in the Bhutan Himalaya. For some dangerous glacier lakes, monitoring is urgently required to prepare necessary mitigation activities.

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