STUDY OF GLACIAL LAKE OUTBURST FLOODS AND METHODS TO PREVENT THEIR EFFECTS

Budhaditya Dutta

Abstract - *Glacial lakes are common in the high elevation of glacierized basin. They are formed when glacial ice or moraines impound water. These lakes normally drain their water through seepage in front of the retreating glacier. Flash floods caused by the outburst of glacial lakes, called as Glacial Lake Outburst Flood (GLOF), are well known in Himalayan terrain, where such lakes are formed due to landslides. Satellite remote sensing-based mapping and monitoring of the glacial lakes and water bodies covering Indian Himalayan region, was taken up. Glacial-dominated areas pose unique challenges to downstream communities in adapting to recent and continuing global climate change, including increased threats of glacial lake outburst floods (GLOFs) that can increase risk due to flooding of downstream communities and cause substantial impacts on regional social, environmental and economic systems.*

1. INTRODUCTION

Glacial lakes are common in the high elevation of Glacierised basin. They are formed when glacial ice or moraines impound water. The impoundment of the lake may be unstable, leading to sudden release of large quantities of stored water. Glacier Lake Outburst Floods (GLOFs) are amongst the most serious natural hazards in the Himalayas. Their unpredicted catastrophic occurrence, their path of destruction which can exceed 100 km downstream the outburst location (Post & Mayo, 1971) and their potential for destruction of settlements and infrastructure have been the subject of numerous papers. Most of the literature concentrates on aspects of historic GLOF events, glacier lake inventories, scientific aspects of GLOF processes and damage mitigation techniques viz: evacuation of populated areas and planning or re-location of infrastructure (roads, bridges). Since 1935, a total of 14 GLOFs have been reported, which either occurred in or extended into Nepalese territory. Most of these GLOFs are well documented; however, records of GLOFs from the West, Far West and Far East of Nepal, here GLOFs are also likely to have occurred, are lacking.

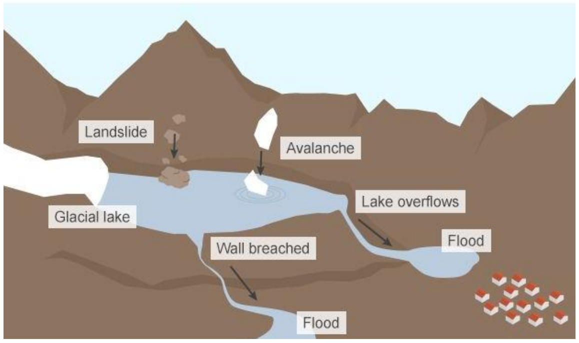

Fig 1. Glacial Lake site

Budhaditya Dutta is currently pursuing bachelor's degree program in civil engineering in Amity University Kolkata, India, PH – 9874246840, email id – bdneil3103@gmail.com

2. OBJECTIVES FOR GLOF CONTROL

The overall objective for GLOF control is defined here as: Glacier Lake Outburst Floods are prevented using methods for the controlled drainage of dangerous glacier lakes.

To achieve this objective, several results have to be obtained.

- An inventory of glacier lakes is prepared and those lakes identified for further investigations which do pose a danger for downstream villages, power stations and infrastructure as well as agriculture. This inventory can be prepared using aerial photography and, where applicable, other remote sensing information.
- A set of indicators has been agreed upon to classify GLOF risk using geomorphological, geotechnical, glaciological and hydrometeorological information gathered on field expeditions and quantitative on-site investigations.
- Methods for controlled lake drainage are compared with respect to on-site feasibility, effectiveness and cost.
- A lake monitoring system is designed and implemented. The monitoring system is used to operate the lake drainage system and the management of the lake which can be considered as a reservoir.
- Depending on the site and downstream conditions, necessary ancillary structures for the use of the lake water are designed.
- Upon the method chosen, the site investigations are completed, the lake drainage designed and implemented.

The activities which are necessary to implement a lake drainage project can only be outlined here in a general way; priority is given to discussion of conventional drainage methods and the presentation of a new technique: the introduction of the Hydraulic Syphon Technique as a method to prevent GLOFs.

3. TYPES AND STABILITY OF GLACIAL LAKES

The assessment of the stability of glacier lakes is an important criterion for the selection of glacier lakes where flood mitigation and/or outburst prevention techniques are to be executed with priority.

Characteristically, glacier dammed lakes can be classified as moraine dammed (with or without ice-core) and glacier dammed lakes - dammed either by active glacier masses or debris-covered ice masses with or without contact with the active part of the glacier. In reality, many combinations are observed. The geomorphological setting of glacier lakes and their hydrological behavior are important general indicators for glacier lake stability. Glacier lakes, which occupy old glacier tongue basins of retreating glaciers, through valley glaciers and cirque glaciers with old, stabilized end-moraines formed during the Pleistocene period are relatively stable and outbursts less likely.

On the other hand, glacier lakes which are in contact with an active glacier and which are dammed by unconsolidated moraines resulting from periods of recent glacier advances in the last 300 years, especially the last "Little Ice-Age" are potentially unstable and more prone for outbursts. These recent moraines have usually steep slope angles and, especially the lateral moraines, slope angles that may exceed the theoretical internal friction value of the moraine materials. The recent terminal moraines have mostly narrow crests and may contain ice lenses or cores.

4. MECHANISMS OF OUTBURSTS FROM GLACIAL LAKES

The mechanisms that lead to an outburst flood can be divided into:

- the triggering event: By far the most common trigger event for a GLOF is a surge wave caused by mass movements like large ice falls, avalanches, slope failures of lateral moraines, rock falls or debris flows into the glacier lake. This surge wave leads to the dam failure. The Sino-Nepalese investigation of glacier lake outburst floods (Chaohai & Sharma, 1988) has stated that bursts of glacier lakes in the Himalayas are mainly caused by the sudden collapse of glacier tongues which result in the instantaneous release of large ice masses into the glacier lake with resultant surge waves and lake overflows. Other triggering events are: overtopping of the dam crest due to lake overflow, intense seepage and piping as a result of a rise in lake water level or melting of stagnant ice lenses in the moraine body. It is apparent that triggering events are related to the hydrometeorological conditions in the area: seasonal rise in temperature and high radiation which increase the melt rate and thus the lake water level. Meltwater also affects the pore water content of unstable masses that may cause slope failures. Meltwater inflow into glacier crevasses with deep crevasse penetration lowers the plasticity of the ice and produces an ice-slide surface at the interface between the glacier and the bedrock.
- the mechanism of dam failure: Only mechanisms of the most common dam failures can be discussed here: site investigations and aerial photos of burst lakes tend to indicate that for most lakes, the surge waves have not directly caused the failure of the dam. Rather than this, they have overtopped the crests of the dams, deepened the existing outflow channel, and then started to erode the leeward side of the moraines. In this way, a channel is formed which, due to the steep slopes, rapidly extends backward by regressive erosion (cf. Lliboutry et al, 1977). After reaching the lake itself, a great part of the moraine collapses and will be washed away instantly: an outburst is generated and the corresponding flood starts to surge down the valley picking up increasing amounts of debris. More gradual rises of the water levels, e.g. during melting periods or glacier advances, may lead to increased seepage and piping which can weaken the dam structure and subsequently can result in a local dam failure. This has been reported from the Zhangzangbo glacier lake (XuDaoming, 1988, cit. Mool, 1992).

5. RISK ASSESSMENT OF GLOFs

Unfortunately, there exists no commonly agreed set of indicators to assess the risk of GLOFs from young, moraine dammed glacier lakes. Qualitative methods include risk assessments from aerial photography and field surveys. From empirical evidence with GLOFs in the Himalayas, a set of indicators for visual surveys of high-risk glacier lakes can be outlined:

- lake dammed by young, unstable and unconsolidated moraines;
- lake is in contact with active ice body of a glacier;
- glacier is advancing;
- glacier tongue is steep;
- glacier is dissected by many deep crevasses;
- unconsolidated, high and steep lateral moraines;
- evidence of general slope failures above the glacier lake;
- high lake water levels and strong dam seepage;
- evidence of recent multiple small outbursts.

6. STUDY AREA

The South Lhonak Lake is located at the altitude of 5200 m above MSL and lies in the higher Himalayan belt. The basement rocks in the area are garnetiferous augen gneiss of Kanchenjunga Formation and quartz biotite schist of Everest Pellite Formation. The lake is highly prone to landslide events which may be triggered by heavy rain, seismic activity, and fluctuating permafrost condition in moraines. The outlet of the lake is bounded by a terminal moraine of approximately 150 m height and is being drained by a narrow channel.

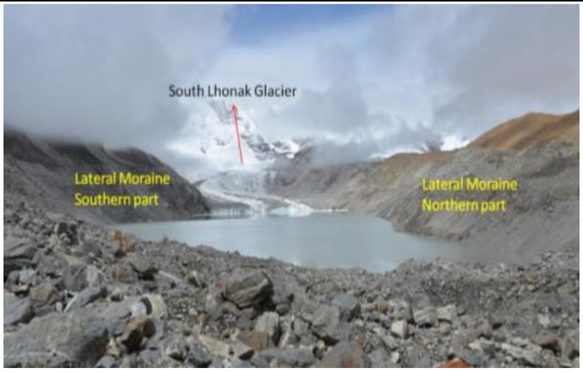

Fig 2. Site of South Lhonak Lake

7. BACKGROUND

- CWC started monitoring of glacial lakes/water bodies in the Himalayan Region of Indian River Basins Since 2009 in association with NRSC, Hyderabad.
- Inventory of Glacial Lakes/Water bodies > 10 ha prepared in June 2011
- Total No. of GL/WB -2028 having size > 10 ha.
- 415 glacial lakes & water bodies with a water spread area more than 50 ha are monitored.
- Apart from this, another 62 glacial lakes & water bodies with water spread area in the range 44 to 50 ha also have been monitored.
- Accordingly, a total of 477 glacial lakes & water bodies were considered for monitoring

BASIN NAME	GLACIAL LAKES	WATER BODIES	TOTAL
Brahmaputra	294	1099	1393
Ganga	178	105	283
Indus	31	321	352
Total	503	1525	2028

Table 1: Basin-wise details of GL[1]/WBS[2]

8. METHODOLOGY

- For the purpose of monitoring glacial lakes and water bodies from satellite images, it is preferable to have cloud free satellite images during the time of monitoring.
- Since the monitoring is carried out during monsoon period, probability of availability of cloud free data is less. Hence all the possible satellite data were browsed and checked for their coverage of the study area and cloud cover.
- The Satellite images of Advanced Wide Field Sensor (AWiFS) of Indian Remote Sensing Satellite Resourcesat-1 is being used for monitoring of GL/WB.

9. METHODS TO REDUCE EFFECTS OF GLOFs

Apart from various kinds of precautions in order to mitigate the effects of potential GLOFs in the areas downstream of the glacial lakes, a series of methods has been proposed to prevent the outburst of GLQF-prone lakes. All these have the aim to lower the water level in the glacier lakes. The main purpose for this is not only the reduction of the water volume but to reduce the hazard of overtopping the morainic dam by surge waves. For water level lowering of glacier lakes the most common techniques are:

- **Artificial deepening of the natural spillway**

This most utilized method consists of the cautions digging down of a breach which enables the water to run off. The hazard of this method is that the run-off of the water can start to erode the spillway and thus get out of control. A disastrous case has been reported by Lliboutry et al. (1977). During the lowering works a huge ice block fell into the lake. The tongue of the glacier had formed a subtle apron sustained by the buoyancy forces of the water. After the lowering, the ice block broke down and the subsequent surge waves swept over the artificial trench eroding rapidly the outside slope of the dam. The resulting GLOF devastated the downstream valley and more than 200 people were killed.

- **Blasting the moraine dam**

In urgent cases, even blasting can be envisaged to cut a trench into dam. Naturally, this can only be done after a series of precautions and after the total evacuation of the downstream area. This can be an interesting solution during an early stage of glacial lake formation.

- **Inclined drilling through the moraine dam**

Instead of digging a trench into the dam, the lowering of the water level can be achieved by the installation of a pipe in the moraine dam. This drilling, however, is rather problematic due to the extremely unsorted and poorly consolidated mass. Blocks of up to several meters in diameter may be encountered and the risk of piping along the casing installed during the drilling is high. To prevent this the surroundings of the pipe should be carefully injected with cement grout. The transport of such equipment to the high and remote areas of the Himalayan glaciers is difficult and expensive

- **Driving a tunnel from an adjacent deeper lying valley (Norwegian Method)**

This very elaborate and safe method has been successfully used, especially in Norway. If the morphology of the surroundings of the glacier lake are appropriate such a solution may be appropriate. In remote areas like the Himalaya with missing infrastructural requirements, however, this system is prohibitively

[1] Glacial Lake
[2] Water Bodies

costly. In Norway, the tunnels are lined with concrete and used as race tunnels to existing hydropower systems.

10. THE HYDRAULIC SYPHON TECHNIQUE (HST)

All methods and techniques mentioned above suffer from unpredictable risks, are too expensive or are too complicated for the harsh Himalayan conditions.

Any optimized method should, therefore, cover the following requirements:

- preservation of the physical and structural integrity of the moraine dam, thus minimizing the GLOF risk
- simplicity and robustness in design and operation
- independence from permanent power supply
- low installation and operating costs

The well-known hydraulic syphon method, used in many fields of hydraulics, seems to fulfil perfectly these requirements and combines their advantage

11. PHYSICAL PRINCIPLES AND OF HST

A hydraulic syphon takes advantage of the difference of a hydraulic potential between the inlet and the outlet of a water-filled pipe. It is able to suck water to a certain vertex from where it runs to the deeper lying outlet.

The maximum possible suction head is a function of the following factors:

- atmospheric pressure (dependent on the altitude, temperature, and its variability due to meteorology processes)
- vapor pressure of the water (dependent on the temperature
- specific weight of the water (dependent on the temperature and on the latitude and altitude of the site)
- internal friction of the pipe system

12. TECHNICAL PRINCIPLES AND DESIGN OF A HST SYSTEM

Most of the Himalayan glacier lakes are situated at levels between 4200 and 5000 m. Therefore, in the appendix, an example is given assuming an altitude of 4500 m. Considering all known factors, a theoretic suction head of 5.5 to 5.75 m for this altitude is the result, depending on the air temperature. Since most of the melting water enters the glacier lake during the warm season, the latter value should be taken for the technical design. Including the factor of atmospheric pressure changes of +10%, a lowering of a lake under the above-mentioned conditions by about 5 m from its spill point level seems to be realistic.

Before any further steps of technical design and installation, this value should be tested on each specific site. For this a simple flexible tube can be used; it must be filled with water, closed at both ends and then laid across the crest of the dam near the spill point. The upper end is put into the lake to the calculated depth and the other end situated several meters below the inlet level. Provided that the tube is free of air and no cavitation occurs due to too high suction heads, the water will flow out of the lower pipe end once the caps have been removed.

To adapt the HST system to a specific site, some more factors must be considered which influence the design and the desired lowering of water level. Among these, the possible height of surge waves originating from ice or rock fall is one of the most important.

13. UTILIZATION OF DRAINAGE WATER

Once the glacier lake has been stabilized against GLOF by controlled drainage, the use of the remaining lake water may be considered. If there is still a difference between the necessary draw-down and the maximum possible suction head, this water volume can be used as a seasonal reservoir. Once the safe water level has been reached, the water flowing into the lake can also be utilized. Possible uses are: micro-hydel generation, irrigation, drinking water supply for people and livestock. The anticipated use of the water will also influence the dimensioning of the pipes and the regulating system to control the drainage volume.

14. CONCLUSION

The improved management of water resources in the Nepal Himalaya must also consider the risks associated with GLOFs. Glacier lake inventories show that there are numerous potentially dangerous lakes in Nepal where a GLOF seems highly probable. There is an acute danger for downstream villages and infrastructure, considering that GLOFs can reach more than 100 km downstream of the outburst site. To ward off GLOF hazards, the controlled drainage of dangerous glacier lakes is proposed. A set of indicators is introduced to assess the risk of moraine dam failure by surge waves. The implementation of classical methods of lake drainage in the Nepal Himalaya is burdened by unpredictable risks, high costs or simply being not feasible in the high altitude, remote regions. Therefore, a new concept is proposed for a controlled continuous glacier lake drainage without the danger of moraine dam destabilization. Its main element is the well-known hydraulic syphon technique which can be adapted to the specific conditions of the high Himalaya. The lowering of lake water levels in the magnitude of 5 m seems to be possible. This can be sufficient to stabilize glacier lakes against outbursts as a result of surge wave action. The hydraulic syphon can be installed relatively easily and does not require permanent power supply for its operation. It must be emphasized that the proposals made in this paper cannot be a blue-print for the design and installation of such a drainage system; rather, they give new impulses to mitigate GLOF hazards and focus the discussion on GLOF prevention instead of on damage control of GLOFs.

For specific site conditions, the use of the drainage water, e.g., for microhydel production may be considered. For the detailed design, testing, installation, operation and monitoring of the hydraulic syphon, the close collaboration of engineering geologists, civil engineers and experts in snow and glacier hydrology is indispensable.

15. ACKNOWLEDGEMENT

The author acknowledges the support of Dr. Dhrubajyoti Chattopadhyay (**Vice Chancellor** of Amity University Kolkata), Dr. Brijasis Pattanayak (**Head** of Amity School of Engineering and Technology Kolkata) and other esteemed faculties of the department in completing this paper.

16. REFERENCE

1. W. E. Grabs, J. Hanisch. Objectives and Prevention Methods for Glacier Lake Outburst Moods (GLOFs).
2. M. A. Somos-Valenzuela, D. C. McKinney, A. C. Byers, D. R. Rounce1, C. Portocarrero, D. Lamsal. Assessing downstream flood impacts due to a potential GLOF from Imja Tsho in Nepal.
3. Deo Raj Gurung, Narendra Raj Khanal1, Samjwal Ratna Bajracharya1, Karma Tsering, Sharad Joshi1, Phuntsho Tshering, Lalit Kumar Chhetri, Yeshi Lotey, Tashi Penjor. Tsho Glacial Lake tburst Flood (GLOF) in Bhutan: cause and impact.
4. Geological Survey of India. Expedition to South Lhonak Lake, North Sikkim