Climate Change and Glacial Lake Outburst Floods (GLOFS) – A Review

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ABSTRACT

The global climatic change during the first half of the twentieth century has brought a tremendous impact on the high mountainous glacial environment. Many of the big glaciers melted rapidly and gave birth to the origin of a large number of glacier lakes. Due to the faster rate of ice and snow melting, possibly caused by the global warming, the accumulation of water in these lakes has been increasing rapidly and resulting sudden discharge of large volumes of water and debris and causing flooding in the downstream. Glacial lake outburst flood (GLOF) causes disasters to life and property along the downstream, results serious death tolls and destruction of valuable forests, farms and costly mountain infrastructure. In this paper a brief review of GLOF and its associated hazards have been discussed in detail.

INTRODUCTION

Concentrations of carbon dioxide (CO_2) and other trace gases in the atmosphere have increased substantially over the last century. Anthropogenic CO_2 emissions due to human activities are virtually, certain to be the dominant factor causing the observed global warming. There are a number of studies to show the increase in temperature particularly since pre-industrial era. Recently, IPCC (2007) has indicated that the average global surface air temperature has increased by 0.74 ± 0.18°C since the late 19th century. The linear warming trend over the last 50 years (0.13[0.10 to 0.16] °C per decade) is nearly twice that for the last 100 years. The rate and duration of warming of 20th century has been found to be larger than any other time during the last 1000 years.

Studies have been conducted to statistically separate out the effects of human intervention from the background "noise" consisting of the natural variability such as changes in the solar radiation and volcanic eruptions. The studies confirm that anthropogenic contributions to radiative forces are already quite significant compared with natural effects. Predictions made by the Global climate models correspond closely enough to the observed patterns of temperature change to confirm that the latter cannot be caused solely by natural phenomena. (Jepma, C. J. and Mohan Munasinghe, 1998)

An analysis of the temperature trend in the Himalaya and its vicinity (Shrestha et al., 1999) shows the temperature changes are higher in the uplands than lowlands. For example, the analysis of temperature trend over the period of 1977 – 94 in Nepal shows warming in most part of the country. High mean annual temperature increases (>0.06degree centigrade per year) occur in most of the northern belt (the Trans-Himalayan and Himalayan regions and central and western parts of the Middle Mountains). Within the Middle mountain region there are two pockets of anomalously high warming rate (>=0.12degree centigrade per year): the western Middle Mountain region and the Kathmandu Valley. Most of the Siwalik and the Terai regions show considerably low increasing trends (<0.03degree centigrade per year).

Due to the climate change and associated temperature increases discussed above, there have been major negative trends in the water system and hazards in recent years. These trends are obvious even to the most casual observers. Retreat of glaciers and increase in size and number of glacial lakes are taking place in the high mountains. Over the years, the alarming recede has been documented by numerous studies. During these studies, satellite data about present area under glaciers has been compared with historical records and fluctuations in temperatures. The results show that recession rate have increased with rising temperature. For example, with the temperatures rising by 1° C, the Alpine glaciers have shrunk by 40 per cent in area and by more than 50 per cent in volume since 1850 (CSE, 2002).

Unpredicted river flows, and frequent floods, droughts and crop failures are becoming frequent events. Many high altitude lakes are potentially very dangerous. Moraine dam glacial lakes are comparatively weak and can break suddenly, leading to the sudden discharge of huge volumes of water and debris. These events are commonly known as glacial lake outburst floods (GLOFs). They can cause catastrophic floodings in the downstreams, with serious damage to life, property, forests, farms, and infrastructure. Shrinkage of glaciers, thawing of permafrost, late freezing and earlier break-up of ice on rivers and lakes, poleward and altitudinal shifts of plants and animals, declines of some plants and animal populations, and emergence of insects have already been observed (IPCC, 2001b). Dokriani Bamak Glacier in Himalayas (India) retreated by 20 meters in 1998, compared with an average retreat of 16.5 meters over the previous 5 years. (Mastny, L. 2000).

In recent years, GLOFs have happened in Nepal, India, Pakistan, Bhutan, and China in the Himalayan region. A list of GLOF events that have occurred in the region are given in the Attachment 4. A huge rapid landslide dammed the Yigong river (China) on 9 April 2000. The Yigong river is one of the second order tributaries of the Yarlung river (upstream of the Brahmaputra river). After two months, on 10 June 2000, the outburst flood from the landslide dam extended 500 km downstream along the Palong and Yarlung river valleys to the state of Arunachal Pradesh, north-eastern India. The outburst flood and damages were on a scale seldom seen before in the region (Zhu and Li, 2001). The GLOF event of 4 August 1985 of Dig Tsho lake at Bhote Kosi destroyed nearly completed small hydel project (estimated cost of US$ 1.5 million), numerous foot-bridges, trekking trails and caused loss of many lives (P. K. Mool, 1993). A list of damage caused by the GLOF events in Himalayas is given in the Table 1 and b.

Table1 (a) : Some recorded GLOF events in Nepal, Tibet Autonomous Region of China and Bhutan (References: Xu & Feng 1994, Mool et.al. 2001)

No	Date	River basin	Lake	Source	Cause of GLOF
1	August 1935	Boqu (Tibet) Sun Koshi (Nepal)	Tara-Cho	Tibet (China)	Dam Piping
2	21 September 1964	PumQu (Tibet) Arun (Nepal)	Gelhaipco	Tibet (China)	Glacier surge
3	1964	Boqu (Tibet) Sun Koshi (Nepal)	Zhangzangbo	Tibet (China)	Piping
4	25 August 1964	Gyrong (Tibet) Trisuli (Nepal)	Longda	Tibet (China)	Not known
5	1968	PumQu (Tibet) Arun (Nepal)	Ayaco	Tibet (China)	Not known
6	1969	PumQu (Tibet) Arun (Nepal)	Ayaco	Tibet (China)	Not known
7	18 August 1970	PumQu (Tibet) Arun (Nepal)	Ayaco	Tibet (China)	Not known
8	3 September 1977	Dudh Koshi	Nare	Nepal	Moraine collapse
9	23 June 1980	Tamor	Nagma Pokhari	Nepal	Moraine collapse
10	11 July 1981	Boqu (Tibet) Sun Koshi (Nepal)	Zhangzangbo	Tibet (China)	Glacier surge
11	27 August 1982	PumQu (Tibet) Arun (Nepal)	Jinco	Tibet (China)	Glacier surge
12	4 August 1985	Dudh Koshi	Dig Tsho	Nepal	Ice avalanche
13	12 July 1991	Tama Koshi	Chubung	Nepal	Moraine collapse
14	3 September 1998	Dudh Koshi	TamPokhari	Nepal	Ice avalanche
15	10 July 1940	Kangboqu-Ahmchu	Qunbixiama-Cho	Tibet (China)	Ice avalanche
16	10 Jul 1954	Nianchu	Sangwang-Cho	Tibet (China)	Glacier advance
17	26 September 1964	Nyang	Damenlahe-Cho	Tibet (China)	Ice avalanche
18	23 July 1972	Xibaxiaqu	Poge-Cho	Tibet (China)	Ice avalanche
19	24 June 1981	Yarlung Zangbo	Zari-Cho	Tibet (China)	Ice avalanche
20	14 July 1988	Palong Zangbo	Mitui-Cho	Tibet (China)	Ice avalanche
21	7 October 1994	Pho Chu	Lugge-Tsho	Bhutan	Moraine collapse

Table1(b) : Some recorded GLOF events and associated damage in Nepal, Tibet Autonomous Region of China and Bhutan (References: Xu & Feng 1994, Mool et.al. 2001)

No	Outburst Lake/ Date/ Basin effected	Losses / damages
1	Tara-Cho; August 1935; Boqu (Tibet) Sun Koshi (Nepal	Debris flood buried farmlands at the mouth of the tributary valley 66,700 m^2 of wheat field, livestock, etc.
2	Gelhaipco; 21 September 1964; PumQu (Tibet) Arun (Nepal)	Debris flood with a peak discharge of 3260m^3s^{-1} at 30 km from the ladke. Damage to Highway and 12 trucks, famland, etc.
3	Zhangzangbo; 1964; Boqu (Tibet) Sun Koshi (Nepal)	Unknown
4	Longda; 25 August 1964; Gyrong (Tibet) Trisuli (Nepal)	Debris flood with peak discharge of 3, 100 m^3s^{-1} blocked Gyiruong (up Trisuli River)
5	Ayaco; 1968; PumQu (Tibet) Arun (Nepal)	Road, bridges, etc
6	Ayaco; 1969; PumQu (Tibet) Arun (Nepal)	Not known
7	Ayaco; 18 August 1970: PumQu (Tibet) Arun (Nepal)	Debris flood formed a new debris fan of 4.6*10^6m^3 near Tingri at 40 km from the lake
8	Nare; 3 September 1977; Dudh Koshi (Nepal)	Mini hydropower plant
9	Nagma Pokhari; 23 June 1980; Tamor (Nepal)	Villages destroyed 71 km from source
10	Zhangzangbo; 11 July 1981; Boqu (Tibet) Sun Koshi (Nepal)	Flood volume of 6.8*10^6 m^3. Debris Flood destroyed the China-Nepal Highway and all the structures within 50 km in the upper valley
11	Jinco; 27 August 1982; PumQu (Tibet) Arun (Nepal)	Debris flood destroyed eight herdsmen villages and killed 1600 livestock, farmland
12	Dig Tsho; 4 August 1985; Dudh Koshi (Nepal)	Hydropower station, 14 bridges, etc.
13	Chubung; 12 July 1991; Tama Koshi (Nepal)	Houses, farmland etc
14	Tampokhari; 3 September 1998; Dudh Koshi (Nepal)	Human lives and more than NRs 156 million
15	Qunbixiama-Cho; 10 July 1940; Kangboqu-Ahmchu (Tibet)	Debris flood buried farmlands at the mouth of the tributary valley
16	Sangwang-Cho; 10 Jul 1954; Nianchu (Tibet)	Debris buried up valley 3 to 5 m thick and flood damaged the cities of Gyangze 120 km away, with a peak discharge of 10,000 m^3s^{-1}, and Xigaze 200km away from the lake
17	Damenlahe-Cho; 26 September 1964; Nyang (Tibet)	Flood volume of 5*10^6m^3. Debris flood dammed up forming a debris dam 20 m high and 850m long at the confluence with Nyang River and stopped the river for 10 hours
18	Poge-Cho; 23 July 1972; Xibaxiaqu (Tibet)	Flood volume of 5.7*10^6m^3. Flood hazard far spread
19	Zari-Cho; 24 June 1981; Yarlung Zangbo (Tibet)	Debris flood destroyed all the local economy constructions in the upper valley.
20	Mitui-Cho; 14 July 1988; Palong Zangbo (Tibet)	Flood volume of 3*10^6m^3. Debris flood with a maximum discharge at about 1,540m^3s^{-1} destroyed a highway 30km long and two villages in the upper valley and caused several people' death.
21	Lugge Tsho; 7 October 1994; Pho Chu (Bhutan)	Loss of life and property along the Punakha-Wangdu Valley and damaged part of Dzongchung of Punakaha Dzong. Twelve housed 5 water mills were totally washed away. 816 acres of dry land were damaged, 965 acres of pasture land damaged, 16 yaks and other livestock, about 6 tonnes of food grains lost

WATER RESOURCES OF THE HIMALAYA

The Himalayan rivers are a source of life-giving water for over 350 million people in north-western, northern and eastern India. The estimate of total surface water run-off of the river systems is given below (Table 2):

Most of the flows in the three systems are contributed by rivers and tributaries originating in the Himalayas. Part of the Ganga's run-off is contributed by rivers draining the Vindhyanchal hills in central India and uplands in south Bihar.

Table 2 : Total surface water runoff of the major Himalayan basins.(Lall, 1981)

Basin	Runoff (*1000 Million m^3)
Indus	209.7
Ganga (at Farakka)	390.0
Brahmaputra (at Bahadurabad, Bangladesh)	606.7

GLACIERS IN INDIA

There are about 9575 glaciers in the Indian Himalayas (GSI, 2007). Out of the total 35,760 km2 area of the Indus and Ganga basin nearly 14.16% is glacierised. The highest number of glaciers (about 1000) is in the Chenab basin. In the Ganga basin excluding Bhagirathi sub basin the glacierised area is about 7.77% of the total area. There are number of glacier lakes identified in the Indian Part of Himalayas. Some of the potential lakes are given in the following Table 3.

Table 3: Glacial Lakes in The Indian Himalayas

S.No	Basin	No of Glacial Lakes
1.	Tons	12
2.	Yamuna	8
3.	Bhagirathi	30
4.	Bhilangana	2
5.	Mandakini	10
6.	Alaknanda	43
7.	Pinder	1
8.	Goriganga	10
9.	Dhauliganga	7
10.	Kutiyangi	4
11.	Beas	59
12.	Chenab	33
13.	Satluj	40
14.	Ravi	17
15.	Taklinga	7
16.	Teesta	266

(Source: Inventory of Glacial Lakes, ICIMOD)

CAUSES OF GLOF

A glacial lake outburst flood (GLOF) can occur when a lake contained by a glacier or a terminal moraine dam fails. The bursting of moraine-dammed lakes is often due to the breaching of the dam by the erosion of the dam material as a result of overtopping by surging water or piping of dam material. Earthquakes leading to the slumping of dam material may also cause the bursting of the lake. The drainage of ice-dammed lakes may be due to: flotation of the ice dam, pressure deformation, melting of tunnels through or under the ice and drainage associated with tectonic activity.

The propagation of GLOF surges trigger landslides and bank erosion that temporarily block the surge waves and result in a series of surges as the landslide dam breach. The flood surge can propagate hundreds of kilometers below the glacial lake. Several empirical relationships have been developed from approximate computations of peak release discharges and they indicate that the moraine-dammed lakes may cause peak discharges, which are 10 times higher than the ice-dammed lakes. The damage and constraints are similar to those as in the case of landslide dam bursts.

THREATS TO BIODIVERSITY AND EXACERBATED LAND DEGRADATION

GLOF has now become one of the major threats to biodiversity in the Himalayan region and exacerbates land degradation processes such as landslides, erosion and siltation. The transport of sediment during GLOF events can be exceptionally high with suspended sediment concentrations as high as 350,000 mg/L. Large quantities of materials are eroded from terraces, valley walls river banks and previous fluvial deposits. The vertical and lateral erosion of the stream channel has the potential to destabilize talus slopes, former debris flows and landslides and to initiate new ones. These processes leave an extensive series of unstable slope sections, which are subjected to intermittent movement and become sources of river sediment over several years following the GLOF event. This causes loss of biodiversity and land degradation in the downstream areas.

The Himalayan region harbours some of the world's richest ecosystems in terms of biodiversity. A sharp and distinct contrast characterizes the eastern (warm and humid) and western (cold and arid) limits with a blend of their elements in the center. The proposed study areas are rich in biodiversity. Eastern Himalayas encompassing the Khangchendzonga landscape, for example, is listed among the world's ten most critical hot spots for biodiversity and endemism. Many protected areas are also located downstream of potentially dangerous glaciers. For example Bhutan falls under Eastern Himalaya that has been declared as one of 10 global 'hotspots' for the conservation of biodiversity, with the highest species density in the world. Potentially dangerous glacial lakes are located in the neighbourhood of Jigme Dorji National Park and Bomdeling Wildlife Sanctuary in Bhutan. In Nepal most of the 2.476 million hectares of protected areas are located in the neighbourhood of potentially dangerous glacial lakes. Annapurna Conservation area, Sagarmatha, Makalo Barun and Kanchan Kanga protected areas, for example are in the downstream of potentially dangerous glacial lakes.

Information on the loss of biodiversity and land degradation due to GLOF events in Himalayas and Central Asian mountains does not exist. However, it is estimated that about 20 % of the total geographical areas of Indian Himalaya is degraded (Bahadur, 1997). GLOF events have played a major role in the degradation of biodiversity. In Central Asia, continuous degradation of mountain and forest ecosystems has been revealed even in Pamir and Tien Shan basins with very low population densities: forest and shrub plantations abruptly declined; natural regeneration of coniferous species ceased and pastures have been degrading. During the last decades the juniper areas have diminished. The potential for natural renewal of coniferous forests in Juniper areas either is minimized or lost. Degraded land and fragmented ecosystems are very sensitive to further degradation by flooding, mudflow, sedimentation and landslides due to GLOFs.

ADAPTATION AND MITIGATION OF GLOF EVENTS.

The adaptation and mitigation process of the GLOFs can be broadly categorized in the following manner

1. Creation of a decentralised information system that includes identification of areas most at risk etc., monitoring and early warning (and prediction) and support to decision makers in terms of policy recommendations on adaptation options etc. This will include the information sharing and experiences dissemination about the early warning and adaptation measures for the GLOF events at the local and national levels.
2. Development and testing of adaptation and mitigation measures, such as land use planning for GLOFs, siphoning, pumping, excavation of a channel, etc.
3. Building capacity of national, district and local institutions to access and use this information and measures as well as to provide information on local indicators/ measurements, which would make the system more interactive and easy to update.

CONCLUSIONS

Several GLOF events have been documented in this region in recent years. Some GLOFs are reported to have created long-term secondary environmental degradation physically and socio-economically, both locally and in neighboring downstream countries. For example, GLOF events are reducing water reserves in the mountains. Therefore in long-term it will lead to reduced water flows in the rivers and thereby causing drought, crop failure and poverty. Since such negative environmental impacts are of concern in the regional and global context, an inventory of glaciers and glacial lakes and an assessment of the risks of GLOFs is an important undertaking.

Accurate knowledge of GLOFs will enhance each nation's abilities to deal with them by providing monitoring and early warning systems and a digital repository of valuable knowledge to inform policy on vulnerability, risk and adaptation. While the total number of glaciers and potential GLOF hazards in the region is still unknown, this project will add greatly to the regional and global understanding as well as the identification and testing of adaptation measures to deal with GLOFs. Monitoring, early warning and the identification of adaptation measures at the potentially dangerous glacial lakes and downstream areas are necessary for guaranteeing the safety of the people, settlements, agricultural fields, forest and mountain ecosystem, natural resources and infrastructures (such as roads, bridges, hydro-power stations, etc.) in the downstream valleys of glacial lakes.

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