Review of Studies on Glacier Lake Outburst Floods and Associated Vulnerability in the Himalayas

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Abstract

The present study is based on the reviews of the available scientific research publications and reports on Glacier Lake Outburst Floods events in Nepal and Bhutan. The study explores the nature, causes, occurrence, and impact of GLOF events and assesses the associated vulnerability, and the existing adaptation measures taken in these countries. Recently, these events have become a serious threat to socio-economy and infrastructures in downstream of the snow fed rivers. A few commendable studies indicate glacier retreat, a possible cause of GLOF; but these studies are confined to certain regions and are based on short observations, limited temporal data on hydro-meteorology and the indirect evidences. Therefore, it is still early to make firm conclusions about the state of affairs. However, these studies have made the government and the community aware of the risk of GLOFs, implicated glacier retreat, climate change, and to look for better adaptation measures.

Keywords: Glacier lake, outburst, flood, GLOF hydrology, moraines, glacier retreat, global warming, climate change, vulnerability, adaptation

Introduction

Natural disasters have become a part of the worldwide spectacle of globalization media. The Glacial Lake Outburst induced disaster has also become a part of it. Its impact and risk on the people and economy of the mountain cannot be in no way underestimated. The GLOF events in the Himalayas have been occurring since long as evidenced by many landform features downstream. The accumulation of debris along the Barun Khola valley presents an example of GLOF event. Similarly, the debris accumulation in Pokhara Valley gives clues to the GLOF event, some 450 years ago occurred in the Seti River due to collapse of moraine of a glacier lake in Machhapuchhare Himalaya. In Bhutan, several evidences show that GLOF event have been the common phenomenon in the past, but not recorded in the modern chronicle and known to people. A Swiss, Geologist Augusto Gansser, during his expedition to Bhutan Himalayas in the 1960s and 70s opined that 1957 Punakha flood was due to an outburst from Taraina Tso in western Lunana (Gansser qtd. in Mool et al. 2001).

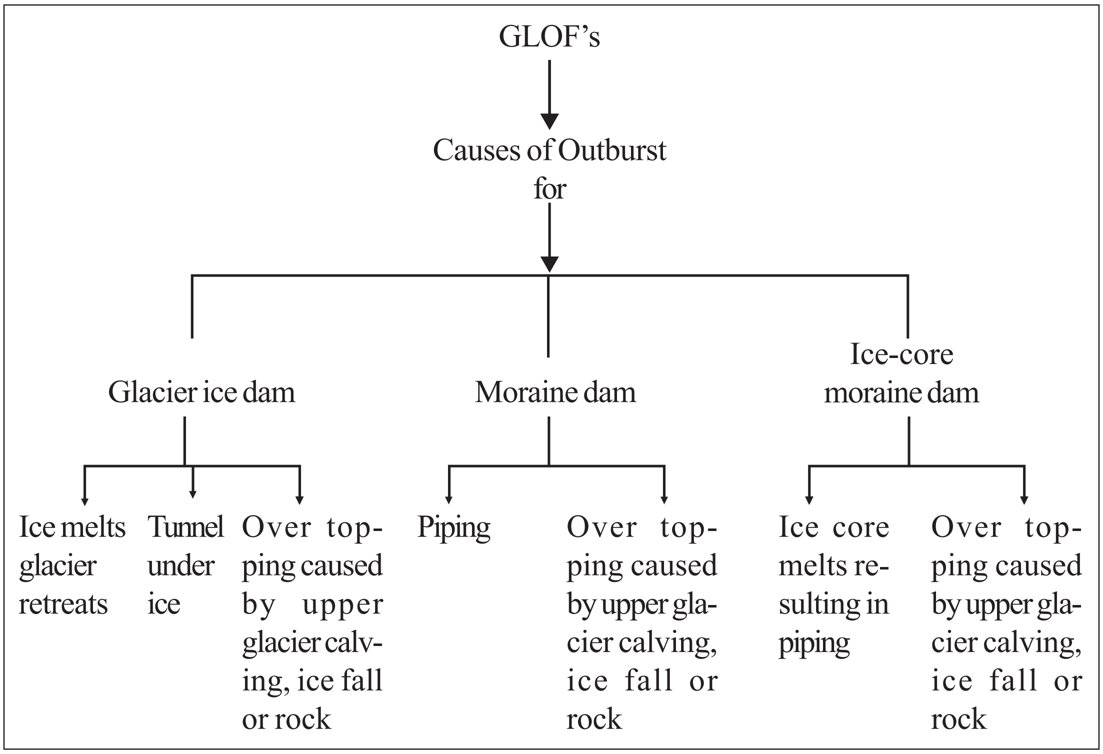
In Nepal, the damage caused by GLOF event could be traced back to 1935 event that occured in Sun Kosi Basin and destroyed cultivated land and livestock. Several catastrophic GLOF events occurred in China and Nepal in 1964, 1977, and 1980 (Yamada 1993) but, these events were not considered seriously. A GLOF event of 1981 in the Boqu River (Sun Koshi) in China was one that slightly raised the concern of development planners and policy makers. It had destroyed a large section of the China-Nepal road as well as the Friendship Bridge, and impacted 30 km downstream in Nepal. Similarly, in 1984 an outburst of glacier lake (Dig Tsho, below Langmoche Glacier in Khumbu) caused a severe disaster to lives and property downstream, and strongly revealed the stakeholders its disaster potential. The lake was drained suddenly and sent 10 to 15 metre high surge of water and debris down the Bhote Koshi and Dudh Koshi rivers, for more than 90 km. An estimated 1 million m^3 of water was released, creating an initial peak discharge of 2,000 m^3/sec; two to four times the magnitude of maximum floods due to heavy monsoon rains. This spectacular natural event destroyed nearly completed Namche Small Hydel project worth NRs 40 million. It destroyed all the bridges 42 km downstream; four or five people lost their lives (Fushimi et al. 1985, Galay 1985, Ives 1986). Similarly, Bhutan experienced GLOF event from partially burst from Lugge Tsho, on October 7, 1994, located in the eastern Lunana (Watanabe and Rothacher 1996). It had caused loss of lives and huge property along Punakha Wangdue Valley. Since then concern about GLOF and its threat to development effort seemed to scaled up among the stakeholders. Consequently, several studies and mitigation effort were carried out (Mool et al. 2001). It is in this context; an attempt made here to review studies and reports on glacier lake outburst flood and associated vulnerabilities in the Himalayas.

GLOF Hydrology

GLOF is a catastrophic discharge of water from the glacial lakes due to failure or breach of ice or moraine dam, formed at the end of these lakes. Such types of sudden discharge from ice and moraine dammed glacier may cause a huge disaster. It is a phenomenon of glacier lakes. a ponding of glacier melt water in depression area of glaciers surrounded by the lateral and end moraines or may formed at the side of lateral moraine of the extended glaciers due to interception of the tributaries by its lateral moraine (Yamada 1993). Among the two types of glacial lakes i.e. moraine dammed and ice dammed, almost all types of glacier lakes in Nepal are moraine dammed. It is because of the fact that the Himalayan glaciers produce very rich debris that make relatively large lateral and end moraine, compared to others glaciers in the world. Ice dammed lakes are very rare, and considered less dangerous for flood hazard (Yamada 1993). Small ponds called as "supra glacier" formed within a glacier may eventually grow and connect each other to form a large lake which might be potentially dangereuous. The history of past glacier lake outburst flood events of moraine-dammed lakes indicates that they are initially derived from supra-glacier lakes (Mool et al. 2001).

Glaciers lakes may not remain as they are all the time. It may disappear when the dam is destroyed or sedimentation fills the lake completely, corresponding to climatic variation (Yamada 1993). During "Little Ice Age" which lasted until 1850, glaciers were extensive. The gradual change in climate, since mid 19th century, majority of mountain glaciers have been thinning and retreating. These events caused the formation of glacier lakes behind the end moraines of the retreated glaciers (Rothlisberg and Geyh 1985). The recent global warming phenomenon have ushered scientist to consider the expansion of glacier lakes and their outburst.

Glacier lakes formation and their outburst are conducive in the High Mountain of Tropics and Subtropics in the Himalayas and Andes. Snow in these areas is very sensitive to small change in temperature. In such areas, small rise in temperature would cause a retreat of glacier and enhances the formation of glacier lakes, at the earlier toe of the glacier, behind end moraine dam. It is reported that glaciers in the Himalayas are 10-25 km length, generally longer than in the Alps, relatively flat longitudinal profile in their lower part. Often they have a large end moraine, which enhances the formation of lakes behind these dams. The gradual rise in the water level of glacier lake may lead to glacier lake outburst flood by over powering the dam due to increasing water pressure (Mool et al. 2001) generally because of warming of temperature, intensive precipitation events, decrease in seepage across moraine due to sedimentation, blocking of an outlet by an advancing tributary glacier, melting of ice-core moraine wall or subterranean thermal activities, inter basin sub-surface flow of water from one lake to another lake due to height difference and availability of flow path, and others local specificities. Glacial lakes' bursting mechanism are as follows:



Studies on Glacier Lakes and Outburst Events in Nepal and Bhutan

Works on glacier inventory in Nepal began in the late 60s. The initiation was made by the Japanese Glacier Research Group (1968-1973) and Glaciological Expedition, Nepal (Higuchi 1976). But these studies virtually did not describe about glacier lakes and their outburst events. Some historical data on glacier lake outburst data was presented in the report of Chinese Investigation Team of 1973/74 (Yang 1994). The catastrophic outburst of Dig Tsho Lake in Eastern Nepal on 4 August 1985, 1977 and 1981 (Galay 1985, Ives 1986) made serious disaster and environmental issue to national and international community as well. This concern heralded a series of studies on glacial lakes in Nepal (Fushimi et al.1985, Galey 1985, Ives 1986) and Tibet and their threat to people and infrastructures at downstream. Government agencies like Water and Energy Commission Secretariat, Nepal Electricity Authority and Chinese counterpart, Lanzhou Institute of Glaciology and Geocrylogy (1988) made a preliminary assessment of glaciers and glacier lakes in the Pumqu (Arun) and Pioque (Bhote Kosi) river basins of China and Nepal with support from Japan International Cooperation Agency (JICA), WECs carried out several inventories of glacial lakes in the Arun, Honku Drangka, Hinku Drangka, Dudh Koshi, Lantang Khola, Chilime, and Marsyangdi Basins through flight observation. The flight observation report recommended detailed examination of the dangerous glacial lakes by site visit. As a result, general feature of several lakes such as Lower Barun, Imja, Thulagi, Dig Tsho, and Tam Pokhari glacier lakes were studied (Table 1).

Much of the studies in the later years were carried on these lakes by semi-government institutes including professional consultancies, individual, and students. Studies of Hammond (1988), Yamada (1993), Watanabe et al. (1994-95) describes about the Imja lake in Khumbu region. From the study of topographic maps, aerial photos, and the imageries, the development of Imja Glaciers have been reconstructed (Yamada 1993). The lake has increased in size from 0.03 – 0.60 km^2 during 1955-1992 (Fig.1). A recent study warns this lake to be potentially dangerous as it is in contact with the tongue of glacier (Mool et al. 2001) which is likely to increase water volume, pressure, and trigger Lake Outburst.

Tsho Rolpa Glacier Lake's geomorphology, development process, hydrometeorology, and hazard assessment is covered in the studies of Damen (1992), Modder and Van Olden (1995), WECS (1993), Reynolds Geosciences Ltd. (1994), Mool (1995a), Budhathoki et al. (1996), Chikita et al. (1997), Yamada (1993, 1998), DHM (1997, 1998, and 2000). Monitoring study of the development process of Tsho Rolpa Lake based on maps, aerial photos and imageries reported that during the period of 1957-1992 the lake increased from 0.23 km^2 to 1.37 km^2 (WECS, 1993) and by 2000 the lake has covered 1.55 km^2 area (Mool et al. 2001).

Studies in Lower Barun Glacier lakes were done by WECS (1993) and NEA (1995). WECS (1993) recommended that the lake is increasing and is associated with larger mother glacier. So, setting any project downstream of Lower Barun Glacier Lake requires detail investigation of the lake and down stream valley.

Similarly, WECS (1995), DHM(1997), Hanisch et al. (1998) had studied Thulagi Glacier. WECS (1995) study reveals the gradual increase of lake during the last 45 years. Comparing the maps of 1958 and field work of 1992 revealed that the lake has increased from 0.22 – 0.76 km^2 and the glacier has retreated by 1.37 km, within the last three decades. However, the study by Department of Hydrology and Meterology (DHM 1997) suggests no danger from the lake in foreseeable future, because it is damed by extended ice bodies which can neither be rapidly breached by lake water pressure or by erosional forces of river. It can only be removed by large scale melting of ice core which requires a period of hundreds to thousand years.

Field investigations to understand the Dig Tsho Lake morphology and outburst mechanism during 1985 was carried by Galey (1985), Ives (1986), Vuichard and Zimmerman (1986/1987), and WECs (1987). These studies suggest being safe until the lake drains completely. However, Mool et al.(2001) argues about the reappearance of lake at the tongue of the glacier. He raised concern about the study of surrounding moraine and the activity of the lake. Dwivedi et al. (1998) reported about the bursting mechanism, discharge of water volume and the loss/damage caused by Tam Pokhari Glacier Lake. Mool et al. (2001), comparing the lakes interpreted on the basis of topographic maps of 1963, 1966, satellite imagery of 1992-93, (based on 1992 aerial photo), found that the lake area had increased from 0.138 to 0.472km^2.

The first glacier expedition made by Gansser (1970) in 1960s identified a number of dangerous lakes, which could flood in the lower valleys. He attributed 1957 flood in Punakha Wangdi Valley to the outburst from Tarina Tsho, western Lunana. In 1970s and 80s, joint study team of Geological Survey of Bhutan (GSB) and the Geological Survey of India (GSI) carried out several investigations to asses hazard and socio-economic risk of glacier lakes in Lunana area. These studies concluded that there was no danger of outburst of Lunana Lake in the near future, but recommended periodic checks in every 2 or 3 years, due to presence of ice cores in the moraine dams. The partial outburst of Lugge Tsho located in eastern Lunana which has affected life and damaged property along the Punakha–Wangdue Valley (Watanabe and Rothacher 1996). Some government agencies of Bhutan carried out research study on cause and effect of outburst and to recommend short and long term mitigation measures (Dorje 1996a, 1996b, National Environment Commission 1996).

Meanwhile, in 1996 after many years gap of first glacier inventory, Phuntso Norbu, Division of Geology and Mines prepared an inventory of glaciers and glacier lakes, which was edited and updated by Geological survey of Bhutan (1999). On the basis of these studies, expansion of glacier lakes were reported by Ageta et al.(qtd.in Mool et al. 2001), Karma et al. (2003). The area of Rapstreng Tsho Glacier Lake in 1986 was 0. 15 $km^{2,}$ in 1960s the lake extended to 1.65 km long and 0.96 km wide and 80 m deep.In 1995 the lake further expanded to the maximum length of 1.94 km, width 1.13 km and the depth 107 km (Fig.1).

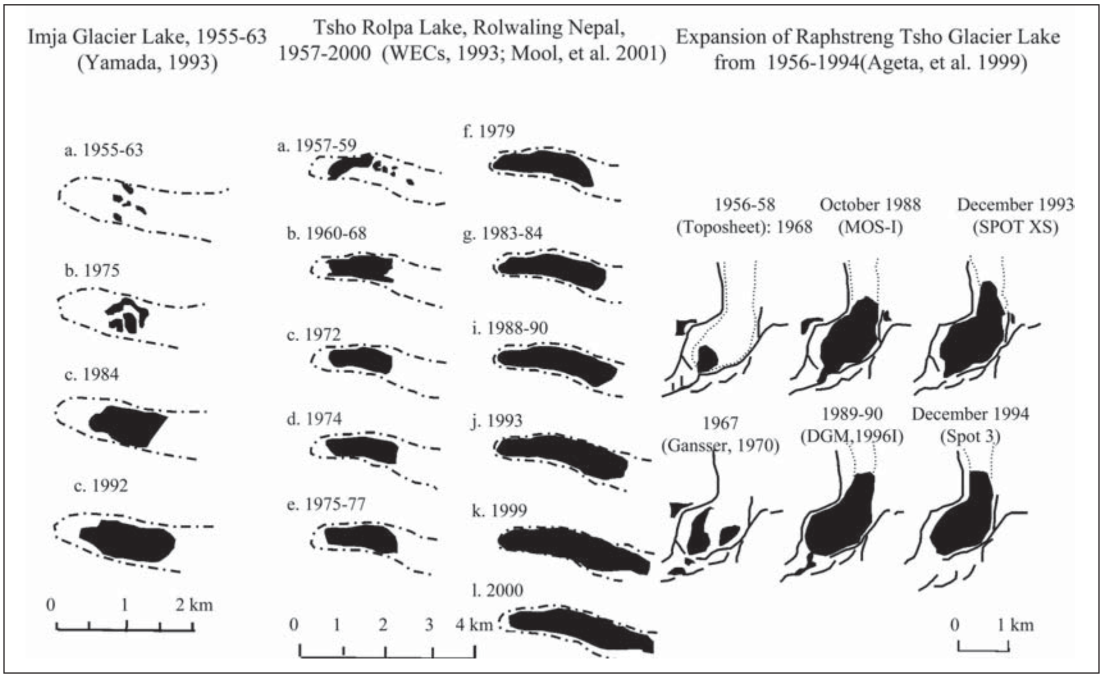


Figure 1. Glacier Lake Development Process

In 2001, international institutions like ICIMOD and UNEP came up with inventory of glaciers and glacier lakes, covering entire part of Nepal and Bhutan, based on the study of topographic maps, aerial photos, satellite imagery and literature available (Mool et al. 2001). The study made total inventory of 3252 glaciers with total area of 5332.89 km^2. These glaciers contain 2323 glacier lakes with total area of 75.70 km^2 in Nepal. Out of them, 20 have been identified as potentially dangerous (Fig. 2). Likewise, in Bhutan, the study found 677 glaciers and 2674 glacial lakes. Total area of glacier was 1316.71 km^2 with ice reserve estimated 127.25 km^2. Of the total lakes 24 were identified as potentially dangerous.

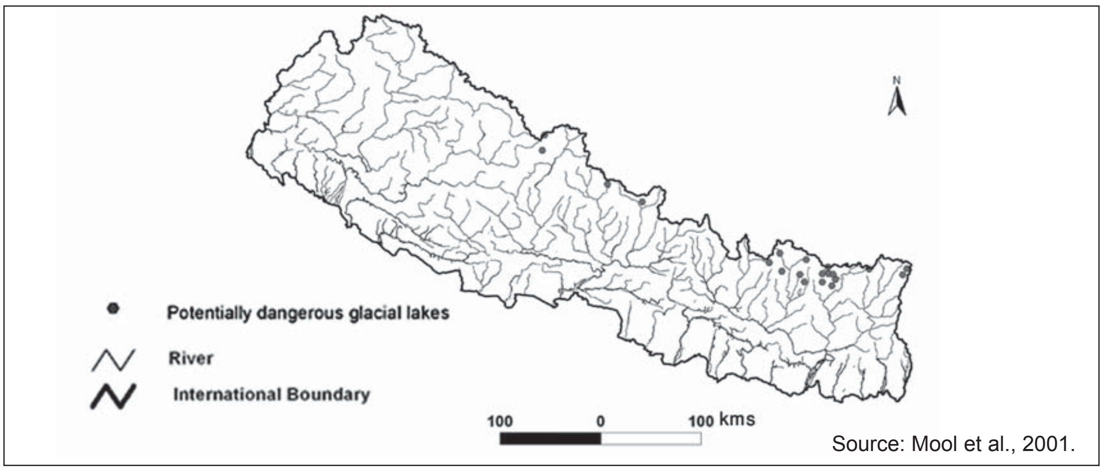


Figure 2. Potentially Dangerous Glacier Lakes of Nepal

Table 1. Locational Aspects of Some Glacial Lakes in Nepal

Features	Lower Barun	Imja	Tsho Rolpa	Thulagi	Dig Tsho	Tam Pokhari
Latitude (North)	27° 48’	27° 59’	27° 50’	28° 30’	27° 52’	27° 44’
Longitude (East)	87° 07’	86° 56’	86° 28’	84° 30’	86° 35’	86° 15’
Altitude (m above sea level (masl)	4570	5000	4580	4146	4365	4432
Depth (m) Average Maximum	50118	47.099	55.1131	41.881	20	45 left after GOLF
Length (km)	1.250	1.3	3.2	2.0	1.21	1.15
Width (km)	0.625	0.5	0.5	0.45	0.44	0.5
Area (km^2)	0.78	0.60	1.39	0.76	0.5	0.47
Stored water (10^6*m^3)	28	28.0	76.6	31.8	10	21.25
Drainage area (km^2)	50	—	77.6	55.4	?	?
Approximate age (years)	35	45	45	45+	50	45+
GLOF release (10^6*m^3)					8	17

Source: Mool et al. 2001.

GLOF Events’ Impact, Vulnerability and Adaptation

GLOF events in the Himalayas not only signify the disaster from flood, but correlate with glacier retreat and global warming trend. The glacier retreat implies a serious concern for water availability for household, agriculture, power and industry for 400 millions living in downstream Indo-Gangetic and Brahamaputra plain. The water demand for agriculture, industry and urban sector in Nepal, India and Bangladesh is progressively growing. The decline in snow cover would mean a condition of water deficit which is a serious threat to food security, energy availability and industry. In the High and Trans-Himalaya region the decline in snow cover would cause serious impact to mountain ecosystem and the livelihood base of the local people which is based on snow melt water fed agriculture and pasture for livestock grazing.

Measured in the term of past damage and loss over the last half century, the damage compared to other natural hazard is less and also less frequent (Table 2). However, the disaster potential of GLOF has increased in recent times due to growth of settlements along the river valleys, construction of motor roads, bridges, and canals at downstream. About 1.56 million people live (within 3 km from glacier fed rivers) downstream of the blocked or moraine dammed lakes within the territory of Nepal (Fig. 4). Several hydropower projects which are either in operation, or under construction or proposed are associated to rivers that have moraine dammed lakes at their head. It is argued that these moraine dammed lakes may develop into potentially dangerous lake. About 5 existing, 1 under construction and 3 proposed hydropower projects are associated to the rivers that have potentially dangerous lakes at their sources within Nepal (Yamada 1993, Mool et al.2001).

Out of those identified as potentially dangerous lakes, mitigation measures of only few have been carried out. In Nepal, Tsho Rolpa is the only glacier lake on which detailed study and mitigation measures are carried out. A first lay man hazard assessment of this lake was done in 1992, and in 1993 a hydro-meteorological station was installed. Later in 1994, a British study team made a scientific study on the assessment of the hazard at Tsho Rolpa. It recommended that the lake level should be reduced by at least 15 m. over 3-5 year (Reynolds 1994). It estimated that occurrence of a GLOF from Tsho Rolpa Lake, could damage up to 100 km downstream from the lake, threatening about 10,000 human lives, thousands of livestock, agricultural land and bridges including some components of the Khimti Hydroelectric Project. As a result, siphons and early warning systems were tested (Mool et al 2001). The first flood warning system in the country was installed in May 1998 to warn the people living downstream from Tsho Rolpa Glacial Lake, in the potential GLOF hit area along the Rolwaling and Tama Kosi Valleys as well as at the Khimti Hydroelectric Project (BC Hydro 1998).

In 1998, the Department of Hydrology and Meteorology, HGM/N under the fund of Netherlands Government, undertook the task of lowering the lake water 3m by cutting an open channel in the end moraine. Likewise in Bhutan as a preliminary stage of planned adaptation to GLOF hazard, studies were carried out since 1970s. Mitigation measures to prevent the bursting of the lake were implemented in 1996 on the Lake Raphstreng Tsho only. In order to lower the risk of flood outburst, the water level of the lake was reduced 4m by excavating channel outlet. In 1999 with an aim to understand more about GLOF hazard, a multidisciplinary approach of assessing geo-risks of the Raphstreng/Thorthormi Tsho area was carried by Austro-Bhutanese Cooperation (Häuslar et.al. 2000). The study concluded that the present day risk for an outburst from Raphstreng is low, but the risk of an outburst of Thorthormi Glacial Lake in the future is considered high. It may occur in 15–20 years if the present trend of climate change continues.

Table 2. Past GLOF Events and Their Impact

Year	River basin	Lake	Source	Losses
1964	Sun Koshi	Tara-Cho	Tibet	6.67ha of wheat field, livestock etc
1964	Arun	Gelhaipco	Tibet	Damaging road, 12 trucks etc.
1968	Arun	Ayaco	Tibet	Road, bridges etc
1977	Dudh Koshi	Nare	Nepal	Mini hydropower plant
1980	Tamor	Nagma Pokhari	Nepal	Villages destroyed 71 km from source
1981	Sun Koshi	Zhangzangbo	Tibet	Hydropower station
1982	Arun	Jinco	Tibet	Livestock, farmland
1985	Dudh Koshi	Dig Tsho	Nepal	Hydropower station, 14 bridges etc
1991	Tama Koshi	Chubung	Nepal	Houses, farmland etc
1998	Dudh Koshi	TamPokhari	Nepal	Human lives and more than NRs 156 million

Source: Yamada 1993, Mool et al. 2001.

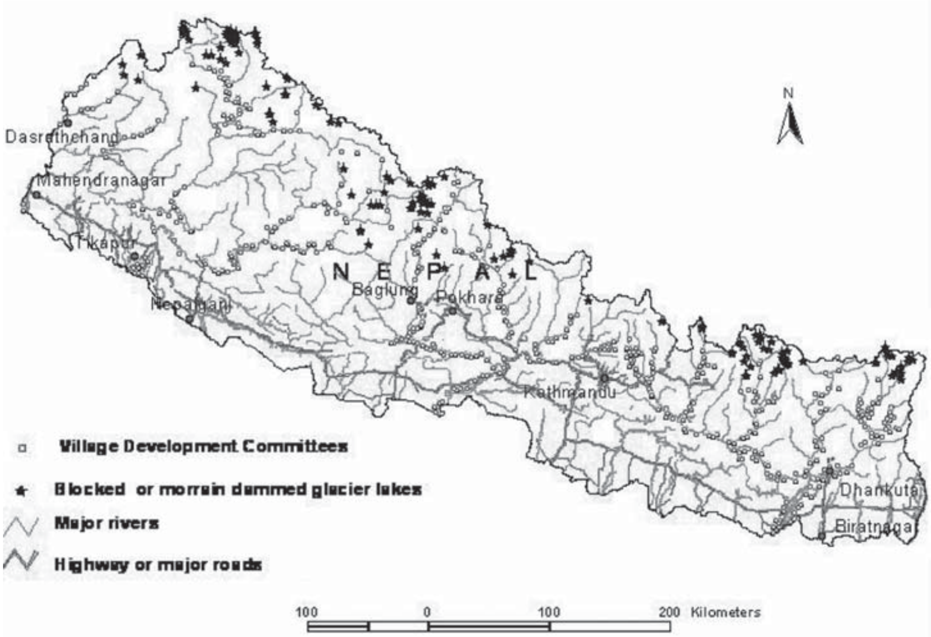


Fig. 3. Potentially Vulnerable Village Development Committees (within 2.5 km distance from the river with headwater associated to dammed glacier lakes)
Source: Survey Department, HMG Nepal; Mool et al. 2001.

Glacier Retreat, GLOF Events and Climate Change

Studies of early 1960s show that the glaciers in the Himalaya have been retreating since the departure of Little Ice Age of the mid nineteenth century (Fushimi et al. 1980; Yamada et al. 1992, Ageta et al.1999, Zhen et al. 2003, Karma et al. 2003). Recent observations have shown many glaciers in the Himalayas retreating rapidly. They are considered to be vulnerable to the recent global warming. Yamada et al. (1992) suggests that the retreating rate in east Nepal has increased in 1980s as compared to earlier decades. This accelerated retreat closely confirms to obvious rise in temperature in Nepal since late 1970s (Shrestha 199, Shrestha 2002). Similarly, glacier retreat in Mt. Sagarmatha has been confirmed by the Sino-American expedition of 1997. It found that since 1966 to 1998 the Rongbuk Glacier has retreated from#Á to 270m which implies the global warming trend. Karma et al. (2002) reveals that the percentage of glaciers retreating in India and Bhutan Himalayas ranges between 87 to 100 per cent, while in East Nepal it is 57.3 per cent (Table 3). The average glacier retreat rate in Bhutan is higher than in east Nepal (Table 4).

Table 3. Tongue Activity of the Glaciers in the Himalayas

Region	Number of glaciers	Retreat (%)	Stationary (%)	Advance (%)
Kashmir	17	100	0	0
Himachal	52	96.2	1.9	1.9
Gharwal	177	97.7	2.3	0
East Nepal	485	57.3	34.9	7.8
Sikkim	255	99.6	0.4	0
Bhutan	103	87.3	12.7	0
Arunachal	62	96.8	3.2	0

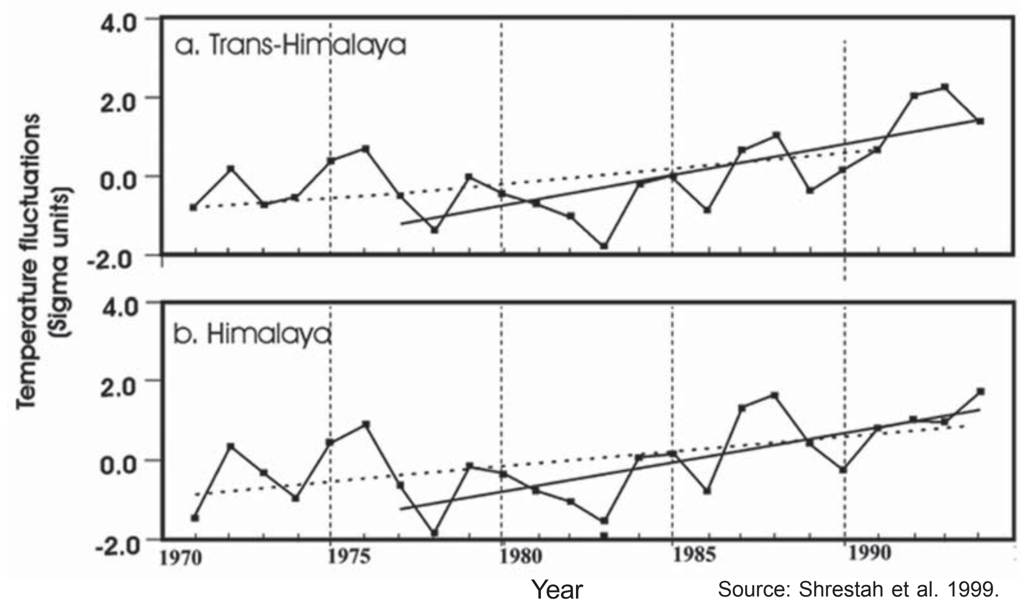
Source: Karma et al. 2003.

Across the Himalayas, global warming is real, and so is the impact. According to the DHM, the temperature is annually rising at the rate of 0.12-degree Celsius in the Nepal Himalayas, while the warming rate for the mid-hills and the Tarai of the country stands at 0.03 degree and 0.06 degree Celsius, respectively.

Table 4. Average Rate of Glacier Retreat in Nepal and Bhutan

Region	Period (Years)	Variation (retreat) rate(m/yr)		No. of glacier
		Vertical	Horizontal	
Nepal	33 (1959-92)	1.72	6.61	58
Bhutan	30 (1963-93)	2.23	7.36	86

Source: Karma et al. 2003.



Source: Shrestah et al. 1999.

Figure 4. Annual Temperature Trends of Trans-himalaya and Himalaya

Since Little Ice Age the total glaciated area in south eastern Tibetan Plateau has been reduced to equivalent of 50 of glacier at present(Zhen and Feng 2000). According to IPCC average air temperature in 2100 AD will be higher than that of 20th century. It is predicted that monsoon temperate glacier area will be reduced 75 % as compared with the glaciers at present. This implies that most temperate monsoonal glacier (Zhen and Feng 2000) and the Himalayan glaciers in the temperate and subtropical location are likely to face same fate. It has been reported that across the Himalayas in Nepal, global warming is real and annual warming rate is 0.12-degree Celsius. The rise in temperature implies that glacier will retreat which will result in the formation of glacier lakes and there is a possibility of their catastrophic outburst, causing significant environmental hazards in many Himalayan valleys (Mool et al. 2001). History of the development processes glacier lakes such as Imja and Tsho Rolpa in Nepal, Raphstreng Tsho Lake, Thorthormi Tsho Lake and Lugge Tsho Lake (Yamada 1993, WECS 1993, Ageta et al.1999) reveal that these lakes have grown considerably bigger in size in 80s.

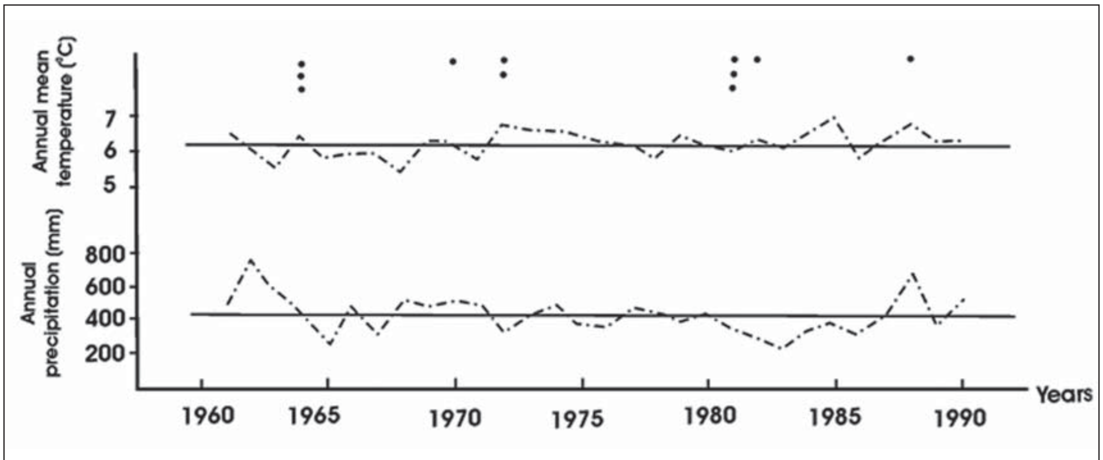


Figure 5. Relation of Outburst Events and Climate Change, Xigatze Climate Stations, Tibet (Xu and Feng 1994).

However, there still exist some anomalies of glacier expansion in some regions, so, linking glacier retreat and glacial formation with global warming is still in premature stage, and therefore, it has to verified by more investigations. It has to be reckoned that some of this warming is part of a natural climatic cycle and the GLOF events in 1964, 1970-1972, 1981-1982 and 1988 (Fig. 6) in Tibetan Himalayas coincide roughly to 10 or 9 year periodicity of climatic variation in temperature and precipitation (Xu et al.1994).

Conclusion

GLOFs have been the common geomorphic events in Nepal and Bhutan, since long. But in recent time, these events have become a serious threat to socio-economy and infrastructures in downstream. The growing population and the expanding infrastructures such as road, bridges and many existing and proposed ambitious hydro-power projects in the river valleys capped by such glacier lakes, have increased the menace of the GLOF hazards in Nepal and Bhutan. This threat implies a serious challenge to the development endeavors. However, the limited studies in GLOFs and glaciers in the Himalayas in terms of space and time, actual threat and vulnerability of the GLOF events is still anticipatory. Hence, more studies should be carried out to cover research gaps.

In recent time GLOF events concur with the glacier retreat which proximate the global warming trend. However, it has to be verified with scientific studies, in future. Glacier retreat and associated environmental issues implies a serious concern for water availability for food security, energy availability, and industries in the down-stream.

A few commendable studies on Himalayan glaciers (since 1970s) and GLOFs (since Late 1980s) has been carried out, but these studies are confined to certain region and are based on short observations, limited temporal data on hydrometeorology and the indirect evidences. Therefore, it is still early to come up with firm conclusions about the state-of-affairs. However, these studies have made the government and the community at large aware of the risk of GLOFs, implicated glacier retreat, climate change, and urged to look for better adaptation measures.

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