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Glacial Lake Outbursts and its Impacts on Human Security in South Asian Countries

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Introduction

Glacier lakes are the most visible and probably the most dramatic consequence of climate change in the mountains. The possible outburst of such lakes is a direct threat to downstream populations and infrastructure. This paper gives an overview of the present situation and the potential danger. It also presents three case studies showing the concrete impacts of glacial outburst.

The dynamic development of glacial lakes and the dramatic consequences in case of outburst has to be seen in the wider context: glacial lakes are the tip of the iceberg of climate change. It can mean the gradual receding of the storage capacity of water in glaciers for the dry season, a quicker runoff of water during monsoon season, and extended days with little water. The long-term consequences affect the availability of water downstream for food production and have direct implications for food security.

Too much water during monsoon and too little during dry season are the scenarios presented by climate change researchers. We have to assume a growing tendency for conflicts around access to water and a direct impact on the most vulnerable segments of the population.

Glacial Lake Outburst Floods in the Greater Himalayan Region

The glaciers of the greater Himalaya [or the Hindu Kush-Himalayas (HKH)] are nature's renewable storehouse of fresh water, from which hundreds of millions of people downstream have benefited annually for centuries when it is most needed – during the dry, hot season before the monsoon. The total number of glaciers in the region is still unknown. ICIMOD initiated the development of a database of glaciers in different basins of the region in a systematic manner using a unified inventory approach.

These high altitude frozen reservoirs release their water at the top of their watersheds. They serve as the perennial sources for the tributaries of ten river basins of the greater Himalayan region that wind their way through thousands of kilometers of grazing, agricultural, and forest land and serve as renewable sources of water for irrigation, drinking water, energy, and industry. In their journey they recharge aquifers and many underground water sources. These glaciers are retreating in the face of accelerating global warming. They are particularly vulnerable to climate change, and the resultant long-term loss of natural fresh water storage will have as yet uncalculated effects on communities downstream. More immediately, as glaciers retreat, glacial lakes form behind some of the now exposed terminal moraines. The locations of such lakes are at elevations ranging from 3000 masl mostly in western part to 5000 masl in the eastern part of the greater Himalaya region. Rapid accumulation of water in glacial lakes can lead to a sudden breaching of the unstable moraine dams. The resultant discharges of huge amounts of water and debris – called a **glacial lake outburst flood** or **GLOF,** a form of flash flood – often have catastrophic effects downstream.

GLOFs are severe geomorphological hazards and their floodwaters can wreak havoc on all human structures located along their path. Much of the damage created during GLOF events is associated with large amounts of debris that accompany the floodwaters. GLOF events have resulted in many deaths, as well as the destruction of houses, bridges, entire fields, forests, and roads. Unrecoverable damage to settlements and farmland can take place at great distances from the outburst source. In most of the events livelihoods are disturbed for long periods. The lakes at risk, however, are situated in remote and often inaccessible areas. When they burst, the devastation to local communities could be tremendous, while those in far away cities downstream may be unaware of the catastrophe. Many glacial lakes are known to have formed in the Himalaya in the last half century, and a number of GLOF events have been reported in the region in the last few decades.

ICIMOD is the first to document systematically glacial lakes and GLOF events in the region. The documents and database give information on glaciers, glacial lakes and areas where GLOF events had occurred, and lakes that could pose a potential threat of a GLOF in the near future**. There are more than eight thousand glacial lakes in the greater Himalaya and about two hundred lakes are potentially dangerous.** This informationprovides the basis for development of a monitoring and early warning system and for planning and prioritizing disaster mitigation efforts that could save lives and properties downstream, as well as guide infrastructure planning. The information is also useful for many of those concerned with water resources and land-use planning. The greater Himalayan region is a model example related to issues on glacial lakes and GLOF phenomena, and ICIMOD has initiated such studies and is playing an important role in coordinating these studies among the states of the region.

Although there are several field evidences of past GLOF events, at least two dozen events in the greater Himalaya have been recorded in scientific literature in the last half century. Some recorded GLOF events, such as from Sangwang-cho in 1954, Xhangzangbo in 1981, Dig Tsho in 1985, Lugge Tsho in 1994, are important to refer to in order to better understand the process and its impact in downstream areas. Statistically seen, the incidence of outbursts has not substantially increased during the last fifty years. What is extremely worrying in the years to come is the increasing number of glacial lakes and their rapid growth.

The 10 July 1954, a destructive GLOF with three hundred million cubic meters of water released from the Sangwang-cho glacial lake in Tibet Autonomous Region of China damaged Nianchu River. Debris buried a valley three to five meters deep and flood damaged the cities of Gyangze 120 km away, with a peak discharge of 10000 cubic meters per second, and Xigaze 200 km away from the lake (Xu and Feng, 1994). The 11 July 1981 GLOF from Zhangzangbo glacial lake in Tibet Autonomous Region of China brought considerable destruction in Tibet (China) and Nepal. It caused severe damage to sections of the Nepal-China Highway including the Phulping and Friendship bridges in Nepal. The road was rebuilt at the cost of US $3 million (Mool, et al. 2001). More damage was brought to the Nepal side during the event. There are several cases of GLOF events where the source was from Tibet Autonomous Region of China but brought more damage in neighbouring Nepal. The 1985 GLOF from Dig Tsho in the Dudh Koshi Basin in Nepal damaged Namche hydropower station (US $1.5 million), 14 bridges, cultivated lands, among others. (Vuichard and Zimmerman 1987). In 1994, Lugge Tsho glacial lake in the Lunana area in Bhutan, formed by the melting of glaciers, burst partially, flooding the Pho Chhu valley and bringing severe damage to Punakha Dzong: it killed 23 people in the Punakha valley and cost the government more than Bhutanese Nu. 43 million in flood relief measures.

Many of the large glacial lakes are on the verge of outburst any time in the future. An outburst from some of the lakes could be catastrophic for downstream riparian areas. For example, a potential GLOF from a Tsho Rolpa glacial lake outburst can damage the settlements at Naa Village located about three kilometers downstream, Beding village, Manthale, Suri Dovan, Nayapul and Kirne, along with vital infrastructure like the Khimti Hydropower Project's tailrace portal and switchyard located eighty kilometers downstream from the lake (Mool et al. 2001). While the tangible impacts are great, particularly along the immediate vicinity of potential impact areas, the effect will even be greater if disruption of goods and services due to damage in infrastructure and communication is considered. Many of the glacial outbursts bear transboundary characteristics.

There are examples of early warning system and GLOF mitigation measures taken in the greater Himalayan region, such as early warning system and GLOF mitigation measures with civil construction work in Tsho Rolpa glacial lake by the Government of Nepal; and Raphstreng Tsho GLOF mitigation with manual excavation by Government of Bhutan.

Threats from possible GLOF events are increasing in the region and require carrying out downstream impact assessment, early warning system, and mitigation measures. Transboundary cooperation is necessary in addressing GLOF issues. Hydropower projects and other infrastructure developments need careful study of GLOF issues in upstream catchments. ICIMOD is promoting regional co-operation in GLOF issues as a platform for sharing knowledge, experiences, information, and raw data. ICIMOD also serves also as a facilitator for monitoring and analyzing changes in glacial lakes and snow and ice in the Himalayas, and conducting downstream impact assessments.

To date, there is no comprehensive record of GLOF events and the damages they have caused in the region. Most of the recorded damage shows the loss of assets/capital, but not the loss of incomes from damaged assets and how this impacts livelihoods over a prolonged time period. Comprehensive economic assessment of damages is necessary in order to weigh the merits of various mitigation policies. The probability of GLOF events are increasing by the day as indicated by records of the formation of new glaciers lakes and the increasing size of older ones. How many people will be affected, what will be the magnitude of such losses, what will be the cost of mitigation – these are important questions that need to be addressed in order to avoid or minimize loss of life and property. Besides physical vulnerability assessments, ICIMOD is also assessing the social vulnerability and long term impacts on livelihoods in GLOF-affected downstream areas.

Three examples of downstream impacts of GLOFs

Case 1: Tsho Rolpa

Tsho Rolpa, the largest glacial lake in Nepal, is currently considered also the most dangerous. This lake has a similar development history as others in the country: it emerged in the 1950s, and grew rapidly in the 1960s and 1970s. The lake expanded to an area of 1.76 km^2 and attained a volume of 92[1] mil m^3 in 2002 (Shrestha et al., 2004). This is the only lake in Nepal where a mitigation measure to reduce the risk of an outburst has been implemented. The measure consists of an open channel dug on the end moraine for water to drain out and the measure has reduced the lake level by 3m. The cost of the mitigation project at completion was US $3.2 million. An early warning system with 19 warning stations was also constructed along the Rolwaling/Tama Kosi Valley with the cost of US$ 1 million. The mitigation measure has reduced the GLOF risk but has not completely averted it. Experts suggest that a further lowering of lake level by 17m would eliminate the GLOF risk.

Before the execution of the mitigation and early warning projects a study was conducted to assess the potential impact of a GLOF from Tsho Rolpa (DHM 1996). However, the study was limited to developing outburst and flood propagation scenarios along the river valley. The results of the study are summarized in Table 1. Independent from the study of DHM (1996), Bhudhathoki et al. (1996) conducted a study along the Rolwaling/Tama Kosi Valley to assess the damage a GLOF from Tsho Rolpa could cause. According to this study, up to a stretch of 63 km (up to Nayapul) the potential GLOF will destroy 15 bridges among which two are highway bridges. The study indicates that about 700 houses and the lives of about 1500 people will be at risk. The study also mapped the area of settlements and agricultural land that can be damaged. The study, however, does not provide estimates of long run damages in terms of lost livelihoods- enterprises, farming lands, public goods, and others.

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[1] This volume was after 3m lowering of the lake level. Without the lowering, the volume would have been 97.7 million m^3.

The then largest hydropower project, Khimti was at risk due to the GLOF from Tsho Rolpa. The risk to Khimti HP, to some extent, played a catalytic role in the implementation of mitigation and early warning measures. Nevertheless, an additional protection measure was adopted at the tailrace part of the project. The scenario has changed drastically in the valley in recent years. Several hydropower projects are in the pipeline. Nepal Electricity Authority (NEA) has secured funding for the Upper Tama Kosi project, a 309 MW hydropower project. This project is estimated at US$ 4.55 billion at completion[2]. While the head works are safe from Tsho Rolpa GLOF, the powerhouse, switchyard and tailrace are at risk (NEA 2004). Similarly, there are at least two other hydropower projects being developed with financing from Norway. Progress is being made in extending the road head further into the valley. The direct impact and secondary socio-economic impacts of the GLOF from Tsho Rolpa could increase many fold in the coming years.

Table 1: Characteristics of Tsho Rolpa outburst flood along the Rolwaling/Tama Kosi Valley.

Location	Distance	Peak Flood (m3/s)	Highest Depth (m)	Time of Arrival of Peak Flood (min)
Just below the moraine	0.00	6460	14.55	0.0
Naa	3.30	6075	12.55	4.8
Beding	10.60	5714	16.05	14.4
Chet Chet	26.15	5348	10.11	28.8
Manthale	38.95	4870	15.03	52.3
Suri Dovan	44.18	4601	11.55	64.7
Nayapul	62.90	3252	9.32	141.9
Sitali	77.11	3017	7.67	191.7
Kirna	80.48	2938	7.39	206.6
Khimti Railrace	81.46	2928	7.79	209.2
Manthali	93.76	2716	4.09	251.5
Beni Ghat	107.02	2061	7.73	343.7

Case 2: Dig Tsho

Dig Tsho bursted out on 4 August 1985. This is the most documented GLOF in Nepal. Vuichard and Zimmermann (1987) assessed the damage caused by the GLOF. The study estimated the peak outflow discharge at 1600 m^3/s. However, a dambreak modeling conducted recently suggested that the peak outflow could have been as high as 5610 m^3/s (Shrestha et al. 2006 and

[2] Kantipur Daily (17 July, 2008)

Bajracharya et al. 2007a). The characteristics of GLOF propagation along the Thame/Dudh Kosi Valley are provided in Table 2. According to Vuichard and Zimmermann (1987), 14 trail bridges were washed away by the GLOF. Further, the flood it caused destroyed 30 houses, among them some newly-built tea houses and lodges. Several sections of trails were also destroyed, compelling locals and visitors to take long and risky detours. Several settlements and lodges were completely cut off for a long time. About 25 to 40 ha of agricultural land were destroyed by the GLOF. The most remarkable impact of the Dig Tsho GLOF was that it destroyed the almost complete Namche Hydropower. The cost of the project at the time of destruction had reached NRs 45 million (US$ 1.5 million).

According to Vuichard and Zimmermann (1987) the GLOF of 1985 was a socio-economic catastrophe for the Khumbu region. Individual families directly hit by the surge lost their entire property (only in some cases was it possible to salvage household effects). One of the severest consequences was that the destruction of valuable cultivable land and forest deprived whole villages of a large part of their subsistence base. Many of the newly build tea shops and lodges along the main trail were cut off, and the owners had to bear the heavy losses. The livelihoods of the community dependent on the trail network were disrupted. The destruction of the hydropower station hampered greatly the expected partial replacement of firewood and thus, the protection of scanty forests.

Table 2: Characteristics of GLOF Dig Tsho GLOF propagation

Location	Distance	Peak Flood (m3/s)	Highest Depth (m)	Time of Arrival of Peak Flood (min)
Just Below the Lake	0	5610	6.17	0
Dig	2	5400	4.5	2.5
Langmoche	3	4986	4.19	4.8
Mingmo	4			
Thamo	7			
Kamthuwa		3592	5.32	9
Hungmo		3300	4.58	13.2
Thame		2897	5.4	21.6
Jorsalle	18			
Chomua	19			
Benkar	20			
Pare		2835	4.97	21.6
Phakding	22			
Tsermadingma	23			
Ghat	25			
Nakjung	30	2145	5.16	60.6

Case 3: Imja Lake

Imja Lake started growing in the 1960s, about a decade later than Tsho Rolpa and Dig Tsho. The lake had an area of 0.83 km^2 and contained 35.8 mln m^3 of water in 2003 (Yamada 2003 and Sakai 005), and based on satellite images the area was estimated at 0.94 km^2 in 2006 (Bajracharya et al. 2007b). The area and water volume are only 47% and 40% those of Tsho Rolpa. Furthermore, the lake is retained by a 600m wide end moraine. Nevertheless, attention towards Imja Lake has been quite high and several studies have been conducted on this lake. Relatively easier access and its location within a prominent tourist destination could have been one of the reasons behind its popularity for monitoring. Earlier, Watanabe et al. (1994 and 1995) conducted a detailed study on the melt rate of the ice under the end moraine. Based on the rates of the westward (edge wards) migration of the shoreline they projected that the shoreline could reach the edge in seven years, or by 2002; fortunately this has not been the case. In recent years, the growth of the lake has been exclusively due to the retreat of a parent glacier at the opposite end.

To estimate the extent of damage of a potential GLOF from Imja, a modeling study was conducted in 2005 (Shrestha et al. 2006, Bajracharya et al. 2007a). The study suggested that the peak flow at the moraine dam could reach 5461 m^3/s. The study further suggested that the outflow could be relatively flat and the breach could be gradual due to the rather large width of the moraine dam. Based on the inundation map prepared by the study it estimated the likely damages to the ecosystem and infrastructure. It was found that the GLOF can destroy 30 houses and 30.32 km of the main trail. About seven trail bridges could be at risk but many of them have been rebuilt at a much higher position after the Dig Tsho GLOF, so not all of them are likely to be washed away. About 90 ha of forest, 29 ha of agricultural land and 25 ha of pasture are likely to be damaged. They represent 3%, 10%, and 7% of these resources, respectively, available along a corridor of 1600m width along the main Imja/Dudh Kosi river valley.

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