Nepal: Responding Proactively to Glacial Hazards

World Resources Report Case Study

SUSAN TAMBI MATAMBO, INDEPENDENT CONSULTANT
ARUN BHAKTA SHRESTHA, INTERNATIONAL CENTRE FOR INTEGRATED MOUNTAIN DEVELOPMENT, NEPAL

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INTRODUCTION

Glaciers hold about 70% of the earth's freshwater (UNEP, 2002). They cover about 17% of the total area of the mountainous Hindu Kush-Himalayan (HKH) region of south and eastern Asia (Xu et al., 2007). Ten of the greatest rivers of Asia have their headwaters in the Hindu Kush-Himalayan Mountains. Thus, these mountains are often called "the water towers of Asia" (ICIMOD, 2009). Nepal is a small land-locked country in South Asia, occupying an area of 147,181 km^2 and with a population of about 29 million people (The World Bank Group, 2009). A major portion of the country's territory is occupied by mountainous terrain, which contains large numbers of glaciers and glacial lakes, as well as being home to 8 of the 10 highest mountain peaks in the world, including Mount Everest (8848 m). Glaciers cover about 9.6% of Nepal's total land area (Sharma, 2010; ICIMOD, 2001). These glaciers are huge reservoirs of freshwater in frozen form which maintain the perennial flow of the major rivers of Nepal as well as the Ganges in India. As a result, changes in the hydrology of Nepalese rivers due to deglaciation could have regional consequences for water resource availability (Germanwatch, 2004).

Glaciers are particularly susceptible to changing temperatures. It has been estimated that temperature rises of 0.04-0.09◦ C/year are occurring in Nepal, with greater warming at higher altitudes (Shrestha et al., 1999; Xu et al., 2007). Warmer temperatures cause accelerated melting of glacial ice, resulting in shrinkage of glaciers. This can lead to the formation of glacial lakes, some of which may burst out and cause flash floods known as glacial lake outburst floods (GLOFs) downstream in the valleys. The potential for loss of life and damage to infrastructure due to glacial lake outburst floods is varied depending on factors such as the size and depth of the lake, the nature of the outburst, the geomorphology of the river valley and elements exposed to the flash flood (Dixit & Gyawali, 1997; Shrestha et al., 2010). It is believed that glacial lake outburst floods may be one of the most important water-induced hazards in Nepal, with the potential to cause large socio-economic impacts in the country (United Nations, 2009; Network-Nepal, 2009).

The Tsho Rolpa glacial lake, situated at the headwaters of the Rolwaling River Valley, is the largest moraine-dammed glacial lake in the Nepal Himalaya. A moraine-dammed glacial lake is formed when piles of rock debris (moraines) impound water behind them. These deposits of debris are accumulated when a glacier retreats and melts over a period of time. Moraine-walled lakes are structurally weak and unstable, so there is significant danger of catastrophic flooding due to slope failure and slumping (Dahal, 2008; Ives, 1986; Rana et al., 2000). Tsho Rolpa is located at an elevation of 4580 m above sea level. The lake has been rapidly increasing in size since the 1950s and currently has a total surface area of 1.65 km^2 (Shrestha et al., 2001). Studies carried out in the early 1990s suggested that the lake had reached a dangerous level and had the potential to burst (Damen, 1992). By the late 1990s, the glacial lake outburst flood hazard became serious and recommendations for lowering the lake water level were made. Glacial lake outburst flood specialist Dr. J. Reynolds warned that the lake might burst in the summer of 1997 (Dixit & Gyawali, 1997).

Proactive decision making in response to risks that are often fraught with uncertainty has historically been difficult for decision makers. Thus, the Nepalese government’s response to the threat of a glacial lake outburst flood occurring from Tsho Rolpa has received acclaim (IPCC, 2007). It was a national-level intervention affecting several districts in the region. The government installed physical structures to reduce the level of the lake and a warning system for residents residing downstream of the lake. Evacuation of the residents living in close vicinity of the lake was also carried out. The whole intervention, particularly the construction of an open channel to lower the glacial lake level, is considered exemplary in the Hindu Kush-Himalaya region, and is believed to have averted a glacial lake outburst flood and reduced the risk for the time being (Rana et al., 2000).

This case study illustrates the proactive response by the Nepalese government to the imminent threat of a glacial lake outburst flood on Tsho Rolpa Lake, and describes the setting and history of this intervention. It also portrays its successes and failures. The intervention taken by the Nepalese government in 1997 was not necessarily a proactive response to long-term climate change, but was rather taken as a disaster risk reduction intervention, aimed at minimizing potential damage to infrastructure and loss of life. This case remains relevant, however, as more is known about the links between deglaciation and climate change; the risks posed to glacial lakes are likely to increase in a changing climate. The Tsho Rolpa case may hold lessons learned for governments and other institutions faced with making decisions due to the threat of glacial lake outburst floods.

SETTING

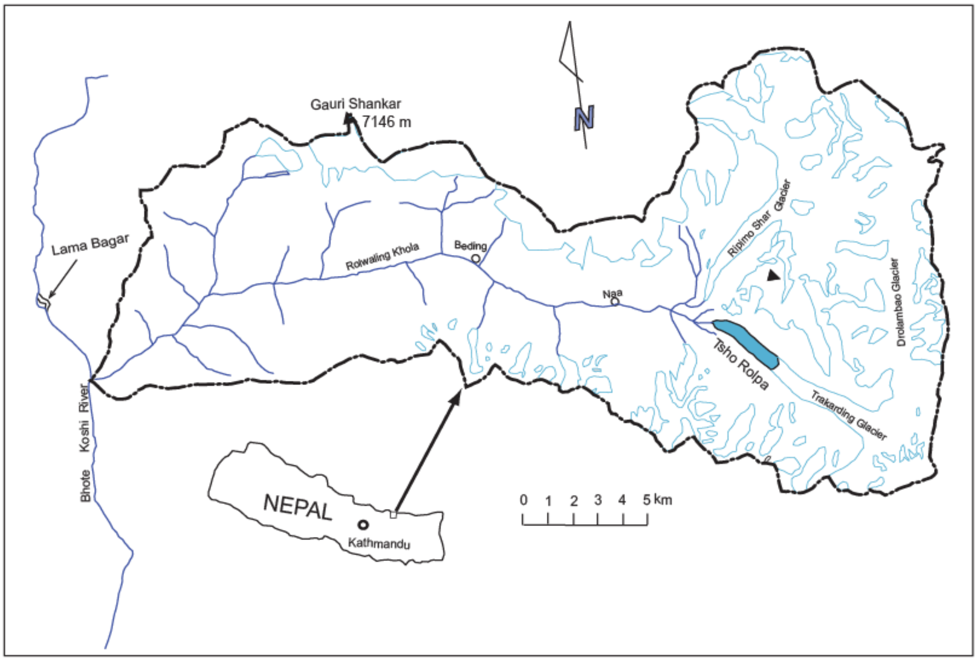

Figure 1: Map showing location of Tsho Rolpa glacial lake (Source: B.S. Rana, 2000)

Tsho Rolpa glacial lake is located about 110 km north-east of Kathmandu in the Rolwaling Valley (Figure 1) at the terminus or bottom end of Trakarding Glacier, at an elevation of 4580 m above sea level. The Rolwaling Valley is oriented in an east-west direction and opens only to the west. It takes 6 days to walk to the lake from Singati, where the nearest road is located.

The creation of Tsho Rolpa Lake was reconstructed by various studies (Figure 2); it is believed to have been formed as a result of retreat, stagnation and melting of the Trakarding Glacier (ICIMOD, 2009; Rana et al., 2000). It is estimated that Tsho Rolpa has been increasing in size since the 1950s: from an area of 0.23 km^2 in 1959 (Yamada, 1998), in 2009 the lake had an area of 1.54 km^2 with a maximum depth of 133.5 meters and volume of 85.94 x 10^6 m^3 (ICIMOD, in prep).

Figure 2 shows that the lake is undergoing constant growth due to intensive breaking away of ice at the terminus of Trakarding Glacier. The total volume of water at present is estimated to be about 80-90 million m^3. The total catchment area of the lake is 77.6 km^2. The temperature around the surroundings of the lake drops to -25◦C in winter and the lake surface freezes by late November. The main inflow into the lake is from the Trakarding Glacier and outflow can reach about 19 m^3 per second during the monsoon season (Yamada, 1998; Dixit & Gyawali, 1997). It is estimated that 7,000 people live along the Rolwaling and Bhote/Tama Koshi Valleys downstream from Tsho Rolpa (Dahal, 2008; Meteorcomm LLC, n.d.).

While this case study focuses on the Tsho Rolpa glacial lake, it is relevant to other glacial lakes in Nepal and the region, and particularly for the communities living downstream of glacial lakes. In 2001, the International Centre for Integrated Mountain Development (ICIMOD), with support from the United Nations Environmental Program (UNEP), identified 2323 glacial lakes in Nepal, twenty of which were categorized as potentially dangerous (Network-Nepal, 2009; ICIMOD, 2001).[1] As a result, several river basins of Nepal are exposed to the threat of glacial lake outburst

[1] The International Centre for Integrated Mountain Development (ICIMOD) has conducted a new study between 2009 and 2010 on glacial lakes in Nepal, however the data is yet to be published.

floods. However, some features of Tsho Rolpa make it the most dangerous glacial lake in Nepal. It is particularly susceptible to outburst as a result of the size of the lake, its rapid growth rate, the presence of numerous icebergs breaking off the glacier causing displacement waves, its high and narrow moraine dam, and the existence of dead ice within the moraine, which is gradually melting.

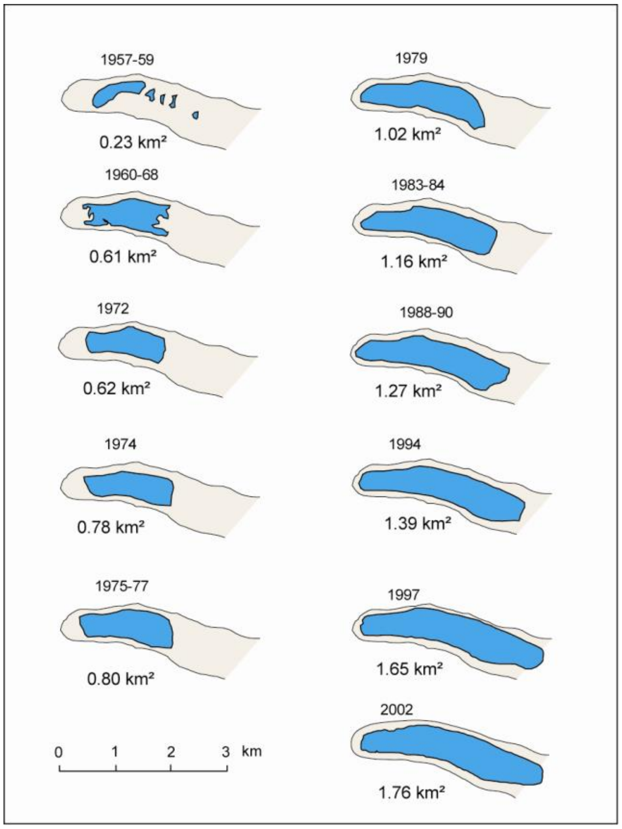

Figure 2: Growth of Tsho Rolpa (Source: Shrestha, M.L. & Shrestha, A.B., 2004)

HISTORICAL CONTEXT

Glacial lake outburst floods are not new in Nepal. There is evidence of a glacial lake outburst flood that occurred some 450 years ago (Dixit & Gyawali, 2007; Dahal, 2008; ICIMOD, 2009). Since 1964, seven major documented glacial lake outburst floods have occurred in the country (Network-Nepal, 2009; see Table 1). Dixit & Gyawali (1997) argue that glacial lake outburst floods first drew the attention of scientists and decision makers only after the disastrous outburst of the Dig Tsho Glacial Lake in 1985. The outburst of Dig Tsho caused devastating financial losses and damage to infrastructure, including a recently constructed hydroelectric power plant, 14 bridges, 30 houses and farmland worth four million dollars, and led to the loss of five lives (Network-Nepal, 2009; Dahal, 2008).

The potential threat of a glacial lake outburst flood from Tsho Rolpa Lake also drew enormous media attention in late 1997 after Dr. Reynolds's recommendations to lower the lake level. The Government of Nepal's reaction was based on scientifically-based recommendations from experts. It is believed that the enormous media attention both locally and internationally could also have contributed to the government's proactive response to the potential threat of an outburst flood from Tsho Rolpa Lake (CNN; Dixit & Gywali, 2007; Discount Pashmina, n.d.).

Table 1: Past glacial lake outburst flood (GLOF) events in Nepal (adapted from ICIMOD, 2010 and Network-Nepal, 2009)

Year	River Basin	Source (Glacial Lake)	Cause of GLOF
1977	Dudh Koshi	Nare Lake	Moraine Collapse
1980	Tamar	Nagma Pokhari Lake	Moraine Collapse
1985	Dudh Koshi	Dig Tsho Lake	Moraine Collapse
1991	Tamakoshi	Chubung Lake	Moraine Collapse
1998	Dudh Koshi	Tam Pokhari Lake	Ice Avalanche
2003	Madi River	Kabache Lake	Moraine Collapse
2004	Madi River	Kabache Lake	Moraine Collapse

RISKS DUE TO CHANGES IN CLIMATE

It is now accepted that the Himalayan glaciers are in a general condition of retreat. While some large and high altitude glaciers in the Karakoram are reported to have advanced (Hewitt, 2007), the majority of glaciers in the eastern Himalaya have retreated in the past decades (ICIMOD, 2009). It is widely believed that changing temperatures may be the cause of the retreat (Bajracharya et al., 2008; ICIMOD, 2009). One of the direct impacts of deglaciation is the formation and growth of moraine-dammed lakes as well as their potential outbursts.

Nepal is highly dependent on rivers fed by glaciers for freshwater resources. For example, hydroelectric power is an important energy source for economic development in Nepal. It has been estimated that Nepal's hydroelectric power potential is about 83,000 megawatts (Shrestha, 1985). However, the installed capacity in the country to date is only 620 megawatts, which is about 0.75% of the theoretical potential. Major increases in hydropower installations are likely in the future (Shrestha, 2010). The majority of planned projects are located near the headwater regions of the Himalayas and several of those projects are envisaged to include reservoirs for storage of hydropower. Consequently, their vulnerability to glacial lake outburst floods is likely to increase significantly (Arya, 2007). Additionally, the nation's economy is overwhelmingly dependent upon agriculture. 80% of the population practices agriculture as a main occupation to sustain livelihoods and about 20% of total area of the land is used for agricultural activities (World Bank, 2007), with farming in the mountains being subsistence-based. Glacial lake outburst floods can have devastating impacts on the livelihoods of the poor and marginal mountain farmers as it can render limited agricultural land useless for many decades and destroy infrastructure. The Dig Tsho glacial lake outburst flood caused damage amounting to about four million dollars to agricultural lands and 30 households downstream (Network-Nepal 2009).

If an outburst of Tsho Rolpa were to occur it would have disastrous wide-scale impacts, due to its topology, location, and the communities and ecosystems dependent upon its water resources (Rana et al., 2000; DHM, 1998). Damage would be felt 100 km downstream (Network-Nepal, 2009). Tsho Rolpa's hazardous glacial lake outburst flood potential was identified as early as 1987, prompting the Water and Energy Commission Secretariat under the Ministry of Water Resources to make detailed investigations in 1993 (Dixit & Gyawali, 1997). Field studies and analyses of the lake's development stages supplemented available maps, aerial photographs and satellite imagery.

At risk are lives, livelihoods, infrastructure such as dams, hydropower stations, biodiversity, water supplies and health. According to a recent study conducted by the International Centre for Integrated Mountain Development, about 5,200 people and 1,150 households are directly exposed to a potential glacial lake outburst flood from Tsho Rolpa Lake. Roughly 46 settlements, 400 acres of agricultural land, 10 km of road, 40 km of foot trails, 16 km of irrigation canals, and 21 trail bridges are at risk of a potential Tsho Rolpa glacial lake outburst flood. Several hydropower stations are in the pipeline for construction and would also be at risk from a flood (ICIMOD, 2009). According to the study, the total value of the elements exposed to potential glacial lake outburst floods was estimated between US$1.85 million and US$8.78 million (ICIMOD, in prep.). Box 1 describes the characteristics of the risks that glacial lake outburst floods pose.

Box 1: The Characteristics of Glacial Lake Outburst Flood Impact Risks

Uncertainty: Even though scientists can approximate that a glacial lake is about to burst, it is not always clear exactly when it could happen. A glacial lake outburst flood can be triggered by various elements such as rock/ice avalanche, earthquake, ice calving. Presence of such elements can be identified but it cannot be predicted when an avalanche or earthquake can occur.

Changes in mean climate system: The formation and growth of glacial lakes in Nepal, including Tsho Rolpa can be attributed to climate change. Studies conducted in the past have suggested that there is significant warming trend over Nepal and the warming rates increase progressively with elevation (A. W. Shrestha 1999, Xu 2007).

Time lag and sudden change: Glacial lake outburst floods build up slowly over time and can occur unexpectedly, causing the need for both long-term preventative measures and fast-reacting mechanisms to contend with these events.

Spatial dimensions (widespread impacts): The spatial dimension of the glacial lake outburst flood impact can be largely variable and will depend on the size of the lake, characteristics of the release of the water, and geomorphologic configuration of the valley downstream. A glacial lake outburst flood includes water flowing at a very high velocity and mixed with large amount of debris. The extent of damage within the impact area can be quite extensive. Further the indirect impact due to loss of transportation means, hydropower generation, etc., can be of national scale (Shrestha et al., 2010; ICIMOD, in prep).

EXISTING POLICY AND LEGISLATION

Upon close examination and according to Shrestha (2010), there is currently no overarching policy or plan that is directly targeting glacial lake outburst flood risk management in Nepal. However, according to the Nepal Disaster Relief Report 2009, there is some sort of intra-governmental coordination for the management of flood-related disasters in Nepal. It is worth mentioning that flood disaster management in Nepal includes prevention, preparedness, rescue and relief, and reconstruction and rehabilitation, which can be applied to glacial lake outburst floods. Local communities are involved at various stages. The following documents and policies in

Nepal do not specifically target glacial lake outburst flood risk management, but they do recognize glacial lake outburst floods within an overall strategy for flood risk management in Nepal. Nevertheless, they may have enhanced Nepal's capacity to manage flood-related disasters. They include:

- Natural Disaster Relief Act, 1982
- National Action Plan for Disaster Management in Nepal, 1996
- Tenth Five-Year Plan (2002-2007)[2]
- National Water Plan, 2005
- Water Induced Disaster Management Policy, 2006
- National Policy and Strategy for Disaster Risk Management, 2007
- National Strategy for Disaster Risk Management, 2009
- Disaster Risk Management Act (draft)

POLICY INTERVENTION

The Government of Nepal in 1997 undertook both short-term and long-term measures to avert a disastrous glacial lake outburst flood event from Tsho Rolpa to reduce the extent of damage that it could cause. Box 2 lists the key players involved in the intervention. The measures taken can broadly be put under three categories:

Physical structures

These were installed to reduce the size of the lake. This included a) installation of test siphons[3] and b) construction of a gated open channel on the moraine for controlled release of lake water to lower the lake level by 3 m. The lowering of the lake was conducted with support from the government of the Netherlands (Dahal, 2008). The construction was completed in 2000.

An emergency warning system

Initially in 1997, the Nepalese government set up temporary army camps at different locations along the Rolwaling Valley downstream of the lake to warn people through Nepal's main radio station that a glacial lake outburst flood event had occurred. This measure was soon withdrawn for a more sophisticated system which was constructed with assistance from the World Bank and installed by Meteorcomm LLC, a private sector company from the United States (Discount Pashmina, n.d.). This system is described below:

1. Installation of an automated glacial lake outburst flood sensor system with support from the World Bank. This included automatic flood sensors located just below Tsho Rolpa to detect changes in outflow from the lake, complete with a redundancy component to minimize false alarms.

2. A telemetric communication system to convey the occurrence of an outburst flood event to warning stations that were installed along the Rolwaling and Bhote/Tama Koshi Valleys. This was installed to warn people if the glacial lake outburst flood event occurred. The warning system was based on a VHF radio technology and would relay any alarm from the sensors located immediately downstream of Tsho Rolpa to the warning stations along the valley. The warning was issued by air horns backed up by electronic sirens (Meteorcomm LLC, 2010). Data management centers were set up to

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[2] This is the first time disaster risk reduction was addressed in planning.

[3] Siphons are high-density polythene pipes placed on the lake. The pipes passed over the moraine ridge to the outer flank of the moraine. Once primed, a vacuum is created due to a difference in pressure in the inlet and outlet, which keeps the water flowing without the need of pumping.

monitor system performance. These were manned by expert personnel.

3. A meteor burst master station which uses the ionized trails of meteors to extend the range of the transmitted radio signals to over 1,000 miles was constructed. Several of the warning stations, as well as a sensing station, transmit and receive signals from the master station, to provide further redundancy to the system in the event that two or more successive stations should fail. The master station also monitors the status of the entire warning system (Meteorcomm LLC, 2010; Bell et al., 1999).

Box 2: Key players involved in intervention

Government: Ultimate decision maker provided the political clout and coordination amongst ministries that was required to respond to threat fairly quickly. The installation of the test siphons and manual early warning system was a coordinated effort of the Department of Hydrology and Meteorology, Nepal Army, Nepal Police, Ministry of Home Affairs, and Department of Water Supply. The Department of Hydrology and Meteorology led the coordination.

Donor agencies: Provided the necessary funding, capacity and installation of the early warning systems. The World Bank provided the funding for the meteor burst early warning system and the Government of Netherlands provided funds for the construction of the open channel through the moraine.

Press: Reported on the threat and provided warning to residents.

Scientists: Performed studies of the lake, bringing in new technologies for survey; risk assessment.

Evacuation

Voluntary evacuation of the inhabitants of the valleys downstream who would have been directly affected by flooding from Tsho Rolpa took place.

The lowering of the lake level at Tsho Rolpa glacial lake is believed to have averted a major disaster. Tsho Rolpa is the only lake in Nepal for which such measures have been taken (Dahal, 2008; Rana et al., 2000; Shrestha & Shrestha, 2004). The construction of an open channel and the set-up of early warning systems took place in the district between 1997 and 1998 (Dixit & Gyawali, 1997). The open channel structures are still functional today. By 2002, however, the Tsho Rolpa early warning systems had ceased to be in operation and there are indications that the threat has long been forgotten by the local communities (Dahal, 2008). Some sources and reports including the Nepal Disaster Report of 2009 indicate that the early warning systems are still dysfunctional today (Dixit, 2011).

DETAILED TIMELINE OF THE TSHO ROLPA GLACIAL LAKE INTERVENTION

A summary of the events that led to the government of Nepal's response to a potential outburst at Tsho Rolpa Glacial Lake is given below.

Research and Recommendations

Preliminary studies of Tsho Rolpa glacial lake began in 1992 after the Chubung glacial lake outburst flood[4] in 1991 (Thomson, 1992). Michiel Damen, a geomorphologist of the International Institute for Aerospace Survey and Earth Sciences ITC in Enschede, Netherlands, prepared the first detailed report entitled "Study on the Potential Outburst Flooding of Tsho Rolpa Glacier Lake Rolwaling Valley, East Nepal" in 1992. He recommended lowering the lake level by several

[4] See Table 1

meters using a siphon over the southwest side of the end moraine. Further, he recommended monitoring the lake level fluctuation and the discharge of the Rolwaling Khola River in the Rolwaling Valley (Damen, 1992).

In 1993, more detailed qualitative and quantitative work was carried out by the Water and Energy Commission Secretariat of Nepal, with support from the Japanese International Cooperation Agency (Mool, 1993). This work included studies of the growth pattern and size of the lake, bathymetric and topographic surveys of downstream villages, and river cross-sections. The Secretariat continued to carry out the studies on glacial lakes and prepared a series of interim reports (Yamada & Sharma, 1993).

A further study of debris flow and hazard assessment due to glacial lake outburst floods in the Rolwaling Valley was also carried out in the mid-1990s (Fujiwara, 1995; J. Reynolds, 1994). Distribution of buried ice was evaluated in 1995 using electrical resistivity exploration at the end moraine of Tsho Rolpa. This study suggested that ice masses were present within the lake.

Modder and Olden, two students from the Free University of Amsterdam, conducted the geotechnical hazard analysis of the Tsho Rolpa Lake. They concluded that on an engineering timescale (50–100 years), the dam was considered to be stable provided that no large-scale events such as earthquakes occurred. However, on a geomorphological timescale (>100 years), moraine dam failure would eventually take place if no counter-measures were taken (Modder, 1995). The study did not take into account climate change.

Rupke and Modder (1996) conducted further research on the geomorphology of the lake, and also performed a geotechnical study. The following year, several reports on Tsho Rolpa were published which included hazard assessments (Reynolds, 1994) and a proposal for lowering the lake level (Reynolds, 1996). The media quickly spread reports that mentioned the possibility of an outburst in the summer of 1997 (Discount Pashmina, n.d.; Dixit & Gyawali, 1997; Dahal, 2008).

Installation of Physical Structures to Reduce the Level of the Lake

In May 1995, test siphons were installed in the southwestern part of the end moraine after a company called WAVIN Overseas B.V. donated specially-designed siphon pipes and couplers to see if they could be used to reduce the level of the lake. The work was undertaken through the Nepal-Netherlands Friendship Association (Rana et al., 2000). In June 1997, the Nepalese government installed five locally manufactured siphons (two with double inlets and three with single inlets) to augment the siphons installed by WAVIN Overseas B.V in 1995. The purpose of installing siphon pipes was to test their performance in the high altitude environment with freezing conditions in the winter. The test siphons worked satisfactorily with some maintenance. The test showed that if funds were available, siphoning out the lake water could be an option to lower the water. However, the siphon option was later dropped due to the requirement of a large number of pipes, the lack of space to install them, and the maintenance required (Discount Pashmina, n.d.).

Figure 3: Open channel constructed in Tsho Rolpa (Source: Arun Shrestha)

In August 1997, a team which included international and national experts visited the lake and recommended lowering the lake level by 3 m by cutting an open channel in the southwest part of the end moraine (DHM, 1997). The Netherlands government funded this project, for which a grant agreement for the Tsho Rolpa Glacial Lake Outburst Flood Risk Reduction Project was signed in August 1998 between the Netherlands and the Government of Nepal. The objective of the 3 m lake lowering was to reduce the water level, which would immediately and tangibly reduce the risk of a breach forming in the natural moraine dam. This flood risk reduction system consisted of a lined channel constructed through the western end moraine (DHM, 1998). The work was 90% complete when construction was halted for the winter shutdown in October 1999 (DHM, 2000). The construction work began again in April 2000 and was completed by the middle of July 2000, lowering the lake level by 3 m (See Figure 3).

Installation of Early Warning and Sensor Systems

In June 1997, the Government of Nepal established an early warning system at Tsho Rolpa, by building a temporary Nepalese Army post at the lake, as well as police posts downstream. These posts were equipped with satellite phones and radios so that inhabitants of downstream locations, as well as the Khimti Hydropower Project, could be informed on a timely basis of a potential glacial lake outburst flood through Nepal's main radio station.

A year later (before the monsoon of 1998), the Department of Hydrology and Meteorology established the meteor burst system, a type of early warning system, to provide the inhabitants of the Rolwaling and Bhote/Tama Koshi Valleys with early information about a glacial lake outburst flood, thereby allowing them time to reach a safe location and save lives and valuables. The timing was critical as the probability of glacial lake outburst floods is higher during the monsoon. The meteor burst system consisted of a glacial lake outburst flood sensing system located just downstream of the end moraine. When a flood is sensed, a warning is relayed to 19 stations located downstream, equipped with audible alarms (see Figure 4). This automated early warning system was established with financial support from the World Bank.

Evacuation of Downstream Residents

Once it was predicted that the lake would burst in the summer of 1997, an evacuation order was issued for residents downstream of Tsho Rolpa glacial lake, in particular for those residing on the banks of the Rolwaling River (Dolakha, 2008.; Dixit & Gyawali, 1997). It is estimated that 74% of the 6000 or so residents moved to safer places for at least one month (Dahal, 2008). Those who responded to the evacuation moved 20 m up from the river bank (Dolakha, 2008).

Figure 4: Tsho Rolpa's early warning system (Source: Arun Shrestha)

OUTCOMES

The structure constructed to lower the lake level at Tsho Rolpa is still perfectly functional. It is believed that the efforts to lower the lake averted the immediate glacial lake outburst flood risk. The water flowing out of the open channel was tapped to run a small micro-hydro plant that has been powering the site, which is manned throughout the year, securing the energy sustainability of the project (Arya, 2007).

However, relocation of residents living within the vicinity of the lake downstream and the implementation of the early warning system have not been a success. First of all, information about an imminent glacial lake outburst flood from Tsho Rolpa trickling from the government to the residents downstream of the lake was largely ignored and dismissed by the residents as "mere rumor" (Dixit & Gyawali, 1997). This was due in part to what some believe to have been exaggeration by the media and in part to cultural norms regarding risk perception (Dixit & Gyawali, 1997; Dahal, 2008). This hindered the process of relocation of the residents to a large extent and was a factor in the somewhat unsuccessful outcome of the early warning systems developed for the Tsho Rolpa case in the long run. Roughly four years after their establishment, the early warning systems that were installed at Tsho Rolpa were no longer operating despite the fact that a robust system was commissioned with the latest technology. Long forgotten by the communities, it lies idle even today (Network-Nepal, 2009).

The sections below discuss the factors that led to policy change and the advancement of interventions to contend with glacial lake outburst flood, as well as hurdles to success, especially with regard to the early warning systems.

REASONS FOR SUCCESS

On close examination, it can be deduced that the measures taken at Tsho Rolpa to avert a potential disaster from a glacial lake outburst flood were successful. The Nepalese government responded proactively to an imminent disaster in 1997 and set prevention and early warning systems in place fairly quickly. The government's ability to collaborate with donor agencies was critical to the rapid pace of developments. Also, scientists were allowed to engage in the policy process, which contributed to the success of this intervention. The project was implemented after a detailed investigation and had a very sound scientific and technical basis (DHM, 1997). In addition, the ability of the Nepalese government to make largely unilateral decisions may have been an advantage (anonymous sources). Also, the local people played active roles in the construction of the physical structures to lower the lake level as well as the early warning systems (Shrestha, 2010). The VHF radio at the lake site was for a long time the only means of communication for the villagers, particularly during emergencies, until mobile phones became common. While seemingly small, this helped establish the importance of the project in the heart of the local people (Shrestha, 2007). Donor funding also was made available fairly quickly to avert the astronomical costs of building structures for reducing the size of the lake and for installing the early warning systems.

REASONS FOR FAILURE

Although the prevention measures were considered a success, the Tsho Rolpa response as a whole was not all successful. Reasons for failure to maintain the early warning systems include the following:

Uncertainty

Predictions about glacial lake outbursts are fraught with uncertainty. This is partly because the literature and science on glacial lake outburst flood hazards is relatively young (Dahal, 2008). Reports claiming that Tsho Rolpa was to burst in the summer of 1997 have been considered unfounded by some (Dixit & Gyawali, 1997; Dahal, 2008).

Participation

There had been some interaction with the villagers in the early days of the construction of physical structures to lower the lake and install the early warning system, and some training was provided on how they should react if the warning siren went off (Shrestha, 2010). However, there were no follow-up interactions and participation in monitoring the early warning systems gradually declined (Dixit & Gyawali, 1997).

Risk Perceptions and Norms

Cultural norms and common folklore in Nepal result in a tendency to "dismiss alarming rumors" (Dixit & Gyawali, 1997; Dahal, 2008). This seemed to have had an impact on the perceived lack of response to warnings by local communities (Dixit & Gyawali, 1997). Apparently, within one month after the warnings, some relocated residents had already returned to their homes (Dahal, 2008). The perception of risk by the residents also seems to have been low. Due to uncertainty about the actual time that a glacial lake outburst flood can occur, there is a high incidence of false alarms (Ives et al., 2010; ICIMOD, 2009; Shrestha et al., 2010). Dahal's 2008 research on risk perception of the communities shows that, "A majority of them demonstrated dissonant risk perception. No adjustments have been adopted by the people at individual level. The low risk perception on the part of the riverine people is chiefly attributed to the cry-wolf effect of the 1997 evacuation that followed the unfounded expert prediction of a Tsho Rolpa outburst."

Communication

There appeared to be a communication gap between experts and the local communities residing in the downstream valleys about the risks that Tsho Rolpa presented. This gap seems to exist today, as some experts have even suggested that Tsho Rolpa be lowered by a further 15 m (Pearce, 2000; Dahal, 2008). Reports of a possible outburst flood from Tsho Rolpa in 1997 often included certain elements of overstatement, in particular by the media (Dixit & Gyawali, 1997). The cry-wolf effect of the evacuation of residents in 1997 possibly led to a "numbing" effect of risk perception of the communities (Dahal, 2008), who today apparently do not perceive Tsho Rolpa as a threat.

Political Unrest

Nepal underwent political upheaval in 1998. According to the International Centre for Integrated Mountain Development (various publications) and Dixit & Gyawali (1997), there has been a lack of institutional capacity to maintain the systems due to political unrest in Nepal for a long period after 1998. The lack of security at large due to the insurgency in the country can also be blamed to a certain extent as this hindered timely maintenance of the system (Network-Nepal, 2009). Some parts of the early warning systems were either stolen or vandalized during the insurgency (C.T.C.S., 2008).

Funding and maintenance

The government did not secure funds for operating and maintaining the warning systems as they require monitoring and maintenance on a fairly frequent basis (Discount Pashmina, n.d.). Without proper maintenance the system has gradually deteriorated to its present non-functional state (Shrestha, 2010). Earlier, a small flood damaged the glacial lake flood sensor, and gradually, it has been reported, equipment from the warning stations has been either vandalized or stolen. Solar panels and batteries were the first to disappear (C.T.C.S., 2008; Shrestha, 2010).

CONCLUSION

Nepal has gained tremendous experience in risk management of glacial lake outburst floods due to past floods and the threat of future events. National-level scientific capability has increased, and capacity is currently being built in local institutions such as universities to increase knowledge. However, with current knowledge and ongoing research about the links between warming and glacial retreat, it is imperative that other countries with similar threats from glacial lake outburst floods seek to partner with research institutions to learn more about glacial lakes and their ability to negatively impact the economy and the people living within the vicinity of the lakes. Currently, researchers from several universities in the United States and Asia are carrying out long-term research on the behavior of glacial lakes in Nepal, particularly on Lake Imja.[5] It is now possible to assess the outburst flood risk of a lake and possible damage to infrastructure and livelihoods to some extent, using remote sensing and mapping. It must however be understood that "precise determination of the degree of risk is not possible. Nevertheless, because it is well-established that glacial lakes have discharged precipitously in the recent past (last 50 years) and caused loss of life and damage to infrastructure farther downstream, it must be assumed that other lakes in apparently similar situations may do so at some time in the future. Such risks must be analyzed (Ives, 2010)."

It is clear from this case study that proactive decision making to prevent possible disaster is imperative. Glacial lake outburst flood risk is a reality in the Hindu Kush-Himalaya region and can be reduced by implementing various structural and non-structural measures. However, the costs of construction of structures to prevent or reduce the damages that can be caused by such outburst floods are astronomically high, particularly for developing countries like Nepal. The physical structures built at Tsho Rolpa required both donor and private sector funding. Nevertheless, proactive responses to threats from glacial lake outburst floods are essential for countries where the risks are high and likely to increase due to glacial retreat as the climate changes.

[5] See University of Indiana, USA; Nagoya University and Kyoto University, Japan.

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