Approaches to Reducing the Hazard of an Outburst Flood of Imja Glacier Lake, Khumbu Himal

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Abstract

Imja Glacier Lake in the Khumbu Himal region of eastern Nepal is a supraglacial lake that is also impounded by ice-cored moraines. Although it appears to be temporarily stable, its size and dynamic nature suggest that an outburst of the lake may pose a serious hazard to the valleys downstream. A simple siphon technique has been proposed to reduce the water level and risk of catastrophe. A warning system for the Imja and Dudh Kosi valleys, using observers and reliable radio and/or sonic communication, is needed until the hazard is reduced. Imja Glacier Lake presents a rare opportunity to actively reduce a serious natural hazard in a mountainous region rather than just respond to the eventual damage.

Introduction

Glacial lakes are found in the high-elevation portion of many river basins throughout the Nepal Himalayas as well as other glacierised areas of the world (Ives 1986). They are formed when water is impounded by glacial ice and/or moraines. There is a wide variety of these lakes, ranging from melt-water ponds on the surface of glaciers to large lakes in side valleys dammed by a glacier in the main valley. With the general retreat of glaciers in this century, a topographic depression is often formed by the moraine at the maximum extent of the glacier. If this enclosure is watertight, melt waters will accumulate in the basin until seepage or overflow limits the lake level. Such moraine-dammed lakes appear to be the most common type of glacial lakes now found in Nepal (Yamada 1993).

In some cases, the impoundment of the lake may be unstable, leading to a sudden release of large quantities of stored water. Failure of these ice or moraine dams as very destructive events has been documented throughout the world (e.g., Ives 1986; Vuichard and Zimmermann 1987). Outburst floods can be several times greater than floods produced by even extreme rainfall (e.g., Dhital et al. 1993). Perhaps the most common trigger of an outburst flood involves surge waves generated by snow, ice, or rock avalanches into the lake that then overtop the dam and rapidly erode the outflow channel, ultimately collapsing the moraine in the vicinity of the channel. Other failure mechanisms include slow melting of an ice core within the moraine, seepage and piping through the moraine, progressive thinning of the moraine by landslides, and earthquakes.

As glacial lake outbursts have threatened more people and property in the Himalayas, they have received increasing outside attention in the past two decades. Damage to bridges, roads, trails, and hydroelectric facilities has generated much of the current interest in these floods. Historical analyses have documented more than a dozen outburst events in Nepal between 1964 and 1991 (Yamada 1993). An outburst flood in 1977 in the Khumbu Himal was recognised in the record of a stream gauging station 60km downstream and was the first event in the region to receive much scientific study. This flood originated from a series of lakes on and below the Nare Glacier in the Mingbo Valley west of the summit of Ama Dablam. Estimates of the volume of water released varied from less than a half million m^3 (Fushimi et al. 1985) to almost five million m^3 (Buchroithner et al. 1982). Nevertheless, erosion of the river channel and terraces in the Imja *Khola* and Dudh Kosi occurred for tens of kilometres downstream.

In 1985, an outburst flood in the Bhote Kosi, a western tributary to the upper Dudh Kosi, received even more international attention because it destroyed a nearly-completed small hydroelectric project valued at about US$4 million. This flood has been thoroughly researched and described in detail (Vuichard and Zimmermann 1987; Ives 1986). In the Langmoche Valley, above the village of Thame, the lake Dig Tsho occupied the moraine-enclosed basin created by the retreat of the Langmoche Glacier. The volume of water stored in the lake was about five million m^3 (Vuichard and Zimmermann 1987). On August 4, 1985, a large ice avalanche impacted the lake and generated a wave about five metres high that overtopped the moraine dam. The dam eroded and collapsed, allowing the lake to drain in four to six hours with a peak discharge of about 2,000m^3s^{-1}. Surveys and mass balance estimates indicated that about 2.6 million m^3 of material were eroded and redeposited within the first 25km (Vuichard and Zimmermann 1987). A dozen bridges and more than two dozen homes were destroyed. Several hectares of agricultural fields were also lost.

An event in the Bhutan Himalayas in October 1994 is the most recent glacial lake outburst flood in the eastern Himalayas (Watanabe and Rothacher 1996). This flood occurred on the Pho Chhu in the Lunana area of northern Bhutan. Small villages close to the outburst source were flooded and incurred some damage, but more than 20 deaths and serious property damage occurred 86km downstream in the village of Punakha at 1,250m. Trees borne by the flood waters contributed to the structural damage (Watanabe and Rothacher 1996).

After the Mingbo and Langmoche outburst floods, Khumbu residents were well aware of the hazard posed by glacial lakes. Some people began to worry about the stability of other lakes in the region. By 1992, several members of the Sherpa community were expressing concern about the lake on Imja Glacier, which threatens the Sherpa heartland. In 1993, a non-governmental organisation was formed by Sherpa people in Solukhumbu and Kathmandu to publicise the hazard and solicit ideas, technical assistance, and financial support to address the problem. This Save the Imja Valley Committee is following the progress of the efforts in Rowaling and is trying to identify appropriate measures for Imja Glacier Lake. This paper attempts to describe the problem to a broader audience of scientists and engineers in hopes of generating creative approaches to this hazard.

Imja Glacier Lake

The development of the lake on the Imja Glacier has been well described by Hammond (1988), Yamada (1993), Yamada and Sharma (1993), Watanabe et al. (1994), and Watanabe et al. (1995). The tongue of the Imja Glacier extends from east to west at an elevation of about 5,100m just south of Lhotse and Island Peak (Imjatse). Photographs and personal accounts indicate that there was no evidence of a lake on Imja Glacier before the mid-1960s, if not later (Yamada and Sharma 1993; Watanabe et al. 1994). During the Japanese Glaciological Expedition of Nepal (e.g., Higuchi 1978), photographs and other observations revealed that a supraglacial lake was forming on Imja Glacier. Photographs from 1980 and 1984 showed that the lake had grown to more than 0.5km^2 in surface area (Watanabe et al. 1994). A survey of the lake in April 1992, including depth measurements, determined it was about 0.6km^2 in area, had an average depth of almost 50m, and contained about 28 million m^3 of water (Yamada 1993; Yamada and Sharma 1993). The lake formed as the debris-covered ice-melted, leaving a depression that collected melt water. A large volume of dead ice mantled with debris downstream from the lake formed the principal dam. Earlier in the lake's development, water apparently spilled over the northern lateral moraine, as indicated by several debris-cone features (Watanabe et al. 1995). However, the lake surface is now about 70m below the crest of the lateral moraines (Yamada 1993). Rapid ice-melt underneath the lake has lowered the water surface elevation below the ground surface beyond the lateral moraine, except near the terminus (Watanabe et al. 1995). Therefore, the possibility of an outburst through the lateral moraines is essentially over.

Unfortunately, the hazard of an outburst remains on the western end where the lake spills through the debris-covered dead ice in a channel about 500-600m long. Surveys of this spillway in 1989 and 1994 show that the ice is melting rapidly and the morphology of this part of the glacier is highly dynamic (Watanabe et al. 1994; Watanabe et al. 1995). These surveys suggest the dead ice along the spillway may be melting at up to two metres per year. The lake shoreline also appears to be migrating westwards. These changes both lower the lake level and reduce the amount of ice impounding the lake. The lake is also expanding to the east as glacier ice-melts, increasing the area of the lake to almost 0.7km^2 (Watanabe et al. 1995). Some seepage was noted exiting from the south-west corner of the terminal moraine in December 1994. The Water and Energy Commission Secretariat has identified Imja Glacier Lake as one of the five most important glacial lakes in Nepal to monitor for signs of increasing risk of an outburst (Mool 1993).

If Imja Glacier Lake was located in a remote, unpopulated valley, an outburst would constitute relatively little hazard. However, the Imja Valley and Dudh Kosi Valley downstream are perhaps the most heavily populated and travelled areas of comparable elevation in Nepal. The Sherpa people have lived in this region for hundreds of years and established villages and agriculture wherever the topography would permit (Brower 1991). River terraces downstream from the Imja Glacier are extensively cultivated. Dingboche is the closest major settlement to the Imja Glacier and is occupied mainly in summer. Farther downstream, the villages of Pangboche, Devoche, and Phunkithangka lie close to the Imja *Khola* (River). Below the confluence of the Imja *Khola* and Bhote Kosi just south of Namche Bazar, where the river becomes known as the Dudh Kosi, the villages of Monjo, Jorsale, Benkar, Phakding, and Ghat are also threatened by a potential flood. Some houses and fields were lost in these lower villages during the Langmoche outburst flood of 1985 (Vuichard and Zimmermann 1987).

The rapid growth of mountaineering and tourism in the Khumbu region during the past two decades has led to considerable development of lodges, businesses, and bridges. The popularity of the area for climbing and trekking creates a large transient population of visitors, guides, and porters in spring and autumn. The principal trail within Sagarmatha National Park follows the Dudh Kosi and Imja *Khola* and crosses each river on several bridges. Supplying the local and visiting population with food, fuel, and other supplies places hundreds of porters on the main trails on any day during the peak seasons.

Reducing the Hazard of an Outburst

Wherever glacial lakes have posed a hazard to people and infrastructure, control measures have been desired. However, implementation has been rare. The basic approaches to reducing the hazard are getting out of the way while letting the natural event take its course, strengthening the dam and providing a reinforced outlet control structure, and artificially reducing the water level of the lake. The last course has been tried in a few instances with varying degrees of success. Where the geology, access, and technology permit, tunnels have been built through solid rock into glacial lakes in Norway and Switzerland. Intentional breaching of a dam in Peru failed with catastrophic consequences when newly-unsupported ice gave way and created a large surge wave (Lliboutry et al. 1977). Explosive excavation of an outflow channel, intended to gradually incise up to 20m depth as lake water was released, successfully emptied seven million m^3 of water in two days at Bogatyr Lake in the Zailysky Alatau of what is now Kazakhstan (Nurkadilov et al. 1986). Other techniques are reviewed by Mochalov and Stephanov (1986) and Grabs and Hanisch (1993).

Siphons carry the least risk of inducing catastrophic failure and are most appropriate for remote installations. Theoretically, lake levels could be lowered about five metres with a simple siphon under Himalayan conditions (Grabs and Hanisch 1993). Siphons have been successfully installed in a lake in the Peruvian Andes near Huaraz where two siphons with a combined capacity of $0.5m^3s^{-1}$

lowered the water level by almost one metre per month (Reynolds 1992 and 1994). However, political strife halted work on the project.

The giant Tsho Rolpa in the Rolwaling Valley, west of Khumbu, has been recognised as a very dangerous lake for several years (Damen 1992; Mool 1993 and 1994). The small outburst of Chubung Lake on the nearby Ripimo Shar Glacier in 1991 served as a reminder of the danger. The Sherpas of Rowaling and Summit Trekking Nepal in Kathmandu publicised the hazard. A study of the potential impacts of an outburst and options for reducing the hazard (Damen 1992) led to the the Wavin Company of the Netherlands donating 500m of 16cm diameter plastic pipe for an experimental siphon system. The first siphon was installed by mid-July 1995 with a capacity of $0.17 m^3s^{-1}$. An outflow of about $1.4 m^3s^{-1}$ would be necessary to lower the level by one metre in one year, without considering additions from rainfall or ice-melt (Damen 1992).

The Save the Imja Valley Committee has endorsed the use of siphons at Imja Glacier Lake and is seeking funding to begin installation in 1996. A principal difficulty with the physical situation at Imja Glacier is the long expanse of dead ice between the lake and valley floor beyond the terminus. A continuous siphon would need to be about 600-700m long. The outlet channel through the dead ice consists of a series of pools that seem to be evolving rapidly. Depending on their shape and depth at the time installation begins, it may be possible to siphon water only a hundred metres or so into a topographically lower pool that is connected to the existing channel. As the volume of water siphoned from the lake increases, the outlet channel may need to be protected against accelerated erosion. Reinforced plastic mats (i.e., hypalon), wire rope, or jute matting may prove to be useful in maintaining a channel. Engineering of an actual siphon and drainage system will require careful surveys of the outlet channel and the flexibility to adapt to the dynamic nature of the glacier's terminus. Every metre of lowering reduces the potential flood volume by 0.5 to 0.7 million m^3. At a net rate of $1 m^3s^{-1}$, the lake could be drawn down by one metre in six to nine days.

Another possible approach to lowering the lake level might be cutting sections of ice in the winter and hauling them over the moraine at a point where it had been excavated manually and with explosives. Where the valley floor beyond the glacier is higher than the lake level, the moraine can be safely removed. Obviously, such actions would be very difficult and expensive. However, the investment in making the Imja Valley safe for habitation and travel should be approached in the manner of a large construction project such as a road or hydroelectric facility. Any operations must be viewed as potentially risky. The possibility of dam failure during lake-lowering activities by initiation of rapid channel incision, glacier calving, mass failure of oversteepened lateral moraines, piping, or earthquakes must be considered. The risk of initiating a failure by action must be weighed against the risk of eventual natural failure. If an engineering approach to lowering the water level proves to be unfeasible, relocation of houses, businesses, bridges, and trails might be contemplated.

As an initial step, a radio warning system should be installed in 1996. Flood warning systems are a potentially valuable interim means of reducing hazards to people (Kattelmann 1994). After approval by the Ministry of Communications, observers would live at the lake and be capable of broadcasting a warning down valley from village to village with a VHF radio and repeaters. If the dam began to be breached, the observers would have the opportunity to give downstream inhabitants some time to move upslope. The speed of the flood wave during the Dig Tsho outburst was estimated at about 14-18km hr^{-1} (Watanabe and Rothacher 1996). If the flood wave from an outburst of Imja Glacier Lake travelled at similar speeds, the principal villages could be reached in approximately 20 to 120 minutes (Dingboche [20 minutes], Pangpoche [40 minutes], Monjo [90 minutes], Phakding [100 minutes]). Any warning system must be carefully designed to ensure proper operation at the critical moment and include significant redundancy to avoid failure. Radio communications failed to provide adequate warning to downstream residents during the 1994 outburst flood in Bhutan because the receiving stations were not manned during the night of the flood (Watanabe and Rothacher 1996). The feasibility of a sound system of multiple relay points might also be explored.

Conclusions

Imja Glacier Lake presents a rare opportunity to actively reduce a natural hazard instead of just responding to the eventual damage. We hope the international aid and development community will act on this opportunity and the similar situation at Tsho Rolpa to avoid impending tragedies. Engineering studies should begin in 1996 to enable lake lowering to begin in 1997. A project engineer, ideally a Khumbu native, should be hired as soon as possible. A detailed survey of the glacier terminus is needed to begin design of a siphon system. Other possible means of lowering the lake level need to be identified and explored. A warning system for the Imja and Dudh Kosi valleys using observers and reliable radio communications is necessary until the risk of an outburst is reduced. Elsewhere in the Himalayas, there may be a few opportunities to deliberately breach moraines that have not yet filled to capacity.

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