High-altitude glacial lake hazard assessment and mitigation: a Himalayan perspective

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Abstract. Glaciers throughout the Himalayas have been receding rapidly over the last few years. In the areas vacated by the ice snouts lakes have formed behind large moraine dams. As with their Andean counterparts, these lakes can pose significant threats to downstream towns, roads and power schemes. For a developing country like Nepal, for example, the prospective loss of economically vital infrastructure and food-producing land can be devastating, in addition to the human misery.

The Tsho Rolpa glacier lake has formed by the retreat of Trakarding Glacier at the head of the Rolwaling Valley in northern Nepal. The lake is now over 3 km long and contains an estimated volume of $8 \times 10^6$ m$^3$. The snout of Trakarding Glacier terminates in the lake which, at its western end, is dammed by an ice-cored moraine. It is feared that the lake could be the source of a major glacier lake outburst flood (known locally as a ‘GLOF’) which could destroy the nearby villages of Na and Beding, as well as trekking routes, vital bridges, etc., further downstream. At Khimti, 80 km downstream from Tsho Rolpa, a new hydroelectric power scheme is being built and could potentially be at risk.

It is known that the local glaciers in the Rolwaling Valley have been the source of many GLOFs in historical as well as contemporary times. The last GLOF destroyed several houses and valuable farm land at Beding in July 1991.

Following an initial GLOF-risk assessment in September 1994, a trial siphon was installed at Tsho Rolpa in May 1995. This is the first time that such measures have been used in the Nepalese Himalayas. Since then further remediation measures have been proposed and are awaiting funding. The nature of the glacial hazards at Tsho Rolpa and the engineering mitigation measures being proposed are described. Furthermore, it is concluded that an integrated national policy on glacial hazards should be developed urgently.

Introduction

Glaciers in the Himalayas have been receding throughout this century. As the ice fronts retreat up valley, proglacial lakes develop behind terminal moraine dams, some of which are cored with stagnant glacier ice. As the volume of stored water increases, so too does the pressure on the moraine walls. In many cases, the moraine fails catastrophically releasing large amounts of water very quickly. Discharge rates of several thousand cubic metres per second are not uncommon. The released water mixes with morainic material to form a highly mobile and devastating debris flow/flood. The name commonly given to this phenomenon is a glacier lake outburst flood (GLOF). In Europe such discharges are known as débâcles; in South America they are referred to as aluviones (Reynolds 1992). They have also been called, erroneously, jökulhlaups (Ives 1986; Benn & Evans 1998); these refer to sub-glacial discharge floods initiated as a result of sub-glacial volcanic activity as occurs in Iceland where the name originated. Although the term GLOF is in essence generic, i.e. it assumes that all such floods originate from glacial lakes, it is perhaps a generalization which does not hold true in all cases.

Glacier lake outburst floods in the Himalayas threaten villages, trekking routes, infrastructure (roads, bridges, etc.), hydroelectric power schemes, and valuable food-producing land. Thankfully, most GLOFs that have occurred in Nepal have been relatively small and the scale of devastation has been limited to areas within the immediate vicinity of the lakes involved. However, one huge catastrophic flood was thought to have occurred about 450 years ago when a lake of some 10 km$^2$ located behind Machapuchhare broke through its ice-cored moraine dam. The resulting flood inundated the Pokhara basin covering it with 50–60 m of debris (Yamada 1993).

Nepal provides a topographic buffer zone between the low plains of India and the high plateau of Xizang (Tibet) in China. For this reason Nepal has played a vital and very valuable role politically, spiritually and economically between India and Xizang (Tibet). Physiologically, river catchments in Xizang provide water in some of the rivers which flow through Nepal and into northern India.

(Chaohai & Sharma 1988). Consequently, catastrophic events in a catchment area in Xizang can have far reaching consequences if the scale of the disaster is large enough. In such cases, run-outs from the source lake may exceed 200 km. Not only does this have economic implications, but also serious political ones too. Furthermore, for an impoverished developing country such as Nepal, which is reliant on food imports to sustain its own population, inward economic investment is crucial. Major infrastructural developments, such as road schemes linking remote areas, and hydroelectric power projects, to name but two, are of critical importance. Yet despite this, there has been little attention paid to the consequences of glacial hazards on such development projects. One reason for this is that the importance of glacial hazards in both the Himalayas and the Andes, for example, is only now starting to be recognized at government level. This recognition is coming about as a result of the increasing amount of literature describing the problems (e.g. Lifboury et al. 1977; Vuichard & Zimmermann 1987; Reynolds 1990, 1992, 1993, 1995, 1998; Grabs & Hanisch 1993) and also because there have been a number of recent glacier lake outbursts which have focused international attention onto the problem. One such example is the potential of a major GLOF from Tsho Rolpa in the Rolwaling Valley (Fig. 1) which is the main subject of this paper. There are others in Nepal which, for reasons of political and commercial sensitivity, will not be addressed here.

**Glacier lake outburst floods (GLOFs) in the Himalayas**

As mentioned above, there have been many GLOFs in Nepal (Table 1; Yamada 1993). However, experience in the Nepal Himal has shown that the geological importance of GLOFs has not been recognized. Not only have there been many more than those recorded (Reynolds Geo-Sciences Ltd 1997), but the scale of some of them in pre-historical times is significantly larger than any of those recorded from historical or contemporary times. The full extent of GLOFs in the geological record has yet to be realized or fully appreciated. They have probably occurred also in Europe and Scandinavia at the edges of the ice sheet as it receded at the end of the last glaciation. In Nepal, a brief trek along one river valley (the Tamba Kosi, Fig. 1) provided sufficient evidence to suggest that there had been many GLOFs there in the past (Reynolds Geo-sciences Ltd 1994).

One of the GLOFs pertinent to this paper occurred in mid-July 1991. Following three very warm days, an ice avalanche fell into Chubung Lake which burst through
<table>
<thead>
<tr>
<th>Year</th>
<th>Location</th>
<th>River system</th>
<th>Principal damage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1980</td>
<td>Phuchan Glacier lake</td>
<td>Sapta Kosi</td>
<td>Damage to forest and river bed, etc.</td>
</tr>
<tr>
<td>1964</td>
<td>Gelpai Lake</td>
<td>Arun/Pumqu</td>
<td>End moraine collapsed due to debris avalanche into the lake; road damaged and 12 trucks lost.</td>
</tr>
<tr>
<td>1968</td>
<td>Ayczio Lake</td>
<td>Arun/Pumqu</td>
<td>Damage to roads and bridges.</td>
</tr>
<tr>
<td>1969</td>
<td>Ayczio Lake</td>
<td>Arun/Pumqu</td>
<td>Damage to roads and bridges.</td>
</tr>
<tr>
<td>1970</td>
<td>Ayczio Lake</td>
<td>Arun/Pumqu</td>
<td>Damage to roads and bridges.</td>
</tr>
<tr>
<td>1982</td>
<td>Jinc Lake</td>
<td>Arun/Pumqu</td>
<td>Moraine collapsed due to glacier tongue sliding into lake. Damage to eight villages, livestock killed, fields, roads and bridges damaged.</td>
</tr>
<tr>
<td>1964</td>
<td>??</td>
<td>Arun/Pumqu</td>
<td>Damage to forest, bridges and trucks.</td>
</tr>
<tr>
<td>1977</td>
<td>Nare Glacier lake</td>
<td>Dudh Kosi</td>
<td>Ice-cored moraine collapsed. Damage to mini-HEP station, road, bridges, fields, etc.</td>
</tr>
<tr>
<td>1985</td>
<td>Dig Tsho</td>
<td>Dudk Kosi</td>
<td>Moraine collapse due to rock avalanche. Destroyed Namche HEP plant, damaged roads, bridges, fields, houses and caused casualties.</td>
</tr>
<tr>
<td>1991</td>
<td>Ripimo Shar Glacier</td>
<td>Tama Kosi</td>
<td>Moraine failure caused damage to trekking routes, killed livestock, damaged fields and houses at Beding village. (See Fig. 2)</td>
</tr>
<tr>
<td>1964</td>
<td>Zhangzangbo Glacier</td>
<td>Sun Kosi/Poiqu</td>
<td>Moraine collapsed due to seepage.</td>
</tr>
<tr>
<td>1981</td>
<td>Zhangzangbo Glacier</td>
<td>Sun Kosi/Poiqu</td>
<td>Moraine collapse due to glacier front calving. Damage to Arniko Highway, bridges, Sun Koshi HEP station, fields, killed livestock and caused casualties.</td>
</tr>
<tr>
<td>1964</td>
<td>Longda Glacier</td>
<td>Trisuli River</td>
<td>No data.</td>
</tr>
</tbody>
</table>

its terminal moraine dam at the southern end of Ripimo Shar Glacier. The breach, which was estimated as being 15 m deep and 20 m wide, is shown in Fig. 2. As is typical of GLOF breaches, a significant debris fan formed immediately downstream of the breach in which the coarser debris load was deposited. The water and finer material travelled downstream past the village of Na, where it killed some livestock and destroyed one bridge, and on through the village of Beding. There it destroyed a number of houses and several valuable potato fields, and caused great alarm amongst the inhabitants.

The event at Ripimo Shar was small in scale yet had sufficient energy to have a run-out of over 10 km. At least four GLOFs have occurred within the Rolwaling Valley in living memory, in addition to that of 1991, although they have not been formally recorded. Evidence of former GLOFs along the Tamba Kosi river valley at distances in excess of 60 km from the nearest glaciers suggests that the area has been affected by much more significant events in the past. There is also possible evidence that GLOF-type flows could have originated within Xizang (Tibet). For example, Lamabaga, a village 5 km N of the confluence of the Rolwaling River and Tamba (Bhote) Kosi, appears to have been built on an alluvial fan/dammed debris flow. If this is the case, then the source of the material must be further north (upstream) from one of the drainage basins inside the Chinese border (Reynolds Geo-Sciences Ltd 1994).

**Glacial hazard assessment and mitigation: Rolwaling Valley**

**Background to the problem at Tsho Rolpa**

Following the July 1991 GLOF from Ripimo Shar, the villages of Beding and Na within the Rolwaling Valley sought outside help as they perceived a serious risk of a future GLOF from Tsho Rolpa, a lake many times the size of Chubung, the source of the 1991 flow. As the Rolwaling Valley is on one of the more serious trekking routes to Mt Everest, Western mountaineers soon learned of the plight of the local Sherpa. Furthermore, letters were written to the principal embassies in Kathmandu requesting help. Dr Michiel Damen wrote
the first formal scientific assessment of the problem in 1992 (Damen 1992). The present author received an invitation to help with the problem at Tsho Rolpa from Dr Damen, and independently from the Water and Energy Commission Secretariat (WECS), Ministry of Water Resources, Kathmandu. WECS had undertaken some preliminary observations in the Rolwaling Valley and around Tsho Rolpa in 1993 (Mool et al. 1993), as had various Japanese researchers funded under a Japanese international aid programme (e.g. Yamada 1993). Given the immediacy of the problem, the author was financed by the Emergency Aid Department of the Overseas Development Administration (now the Department for International Development) to visit Tsho Rolpa and to assess the situation, based on previous experience of hazard assessment and mitigation in Peru (Reynolds 1990, 1992, 1993). As a result of this work, it was realized that the moraine complex that dammed Tsho Rolpa was probably cored with ice. As the maximum amount of freeboard of the moraine dam available during the dry season was about 1 m it was felt that the entire moraine complex, coupled with the volume of stored water within the lake (c. $80 \times 10^6$ m$^3$; Yamada 1996), formed a highly unstable and potentially lethal situation. It was felt that, unless appropriate remediation works were undertaken, the moraine would fail and the Rolwaling Valley would be inundated, causing widespread loss of life and serious damage to local infrastructure. At Khimti, 80 km downstream from Tsho Rolpa, a new hydroelectric power scheme is under active consideration. Subject to financing provisions, it is anticipated that, at the height of construction, some 1500–2000 workers will be housed in a camp adjacent to the river and could potentially be at risk. It has been estimated by the plant managers that serious GLOF damage could cost in excess of $22 million and put the construction project back by two or more years.

Figure 3 shows the view from Na towards the eastern end of Rolwaling Valley. The breach through which Chubung Lake discharged from Ripimo Shar is obvious. The existing spillway from Tsho Rolpa is indicated by an arrow. The height of the moraines above the valley
floor is of the order of 200–250 m. The local geography of Ripimo Shar and the western terminal moraine complex of Tsho Rolpa is shown in Fig. 4. More details of the background to this project have been given by Reynolds (1995).

**Hazard assessment**

The immediate requirement of the field visit in October 1994 was to assess each of three areas; namely, the lake with its moraine complexes, the Trakarding Glacier ice front (which terminates at the eastern end of Tsho Rolpa), and the immediate area surrounding the site. It was important to determine if there was any evidence to suggest the presence of an ice core and its state, to gauge the stability of the moraine complexes (any evidence of slope failure, cracking, anomalous vegetation patterns, differences in material types, etc.) and to inspect the surrounding hanging glaciers as to their common mode of ablation (melt run-off, evaporation, ice calving, etc.). It was also vital to assess the stability of the Trakarding Glacier ice front. Was the glacier grounded or was the tongue afloat in the lake? This question needed to be answered if safe mitigation measures were to be implemented.

In essence, it was concluded from the field visit that the terminal moraine is ice cored in two locations. Evidence for this consisted of hummocky topography, cracked and slumped ground, debris patterns, the presence of sinkholes (drainage through melting ice), etc. Subsequent geophysical resistivity experiments confirmed the presence of massive ice beneath the western end of the lake and into the moraine (OYO Corporation 1995). A simple map of the principal features is shown as Fig. 5, including the interpreted lateral extent of the buried ice. The lateral moraines on the northern and southern sides of the lakes are generally ice-free but are inherently unstable on the lakeside as evidenced by the total lack of vegetation and the constant stream of spalling debris. The outer flanks are much more stable as indicated by almost total vegetation cover.

The Trakarding Glacier ice front was found to be made up of two glaciers that had merged several
kilometres upstream to the east. The northern part of the ice front appeared to be grounded and had a sub-glacial discharge portal evident (Fig. 6; arrowed). The southern part of the ice front was observed to be almost vertical (Fig. 6) and showed signs of cracks parallel to the ice front. Sub-glacial discharge was seen to emanate from below the lake surface at the southern edge of the ice. The form of the ice front indicated its general stability but that relatively small ice avalanches of the order of 1500–5000 m³ were likely to occur. While these in themselves are not particularly troublesome, the lack of freeboard at the terminal moraine to contain the displacement waves from overtopping the moraine is more serious.

The hanging glaciers on the northern side of the lake were found to be relatively well contained with only sporadic ice avalanches, most of which appeared to be contained locally without direct access to the lake below. The local glaciers on the southern side were found to be set further back from the lake so avalanching was not perceived to be a significant problem. As with any high-altitude mountain range such as the Himalayas or Andes, the extremely steep slopes and the sheer vertical scale provide spectacular snow and ice avalanches that occur frequently most days (Fig. 7).

**Hazard mitigation**

From the assessment of Tsho Rolpa and its immediate environs it was concluded that mitigation measures should be implemented as soon as was practical. The most cost-effective and practical way to achieve immediate relief from the threat of the moraine being overtopped was by installing a siphon (Grabs & Hanisch 1993; Reynolds Geo-Sciences Ltd 1994). This was the first stage used in a similar project in Peru (Reynolds et al. 1998). Whatever was decided, it had to be practically feasible and within the constraints of local transport, i.e. carried on the backs of local porters. With support from WAVIN Overseas BV, a Dutch pipe manufacturer, it was agreed that a trial siphon would be installed before the 1995 monsoon. This was achieved using a 16 cm diameter pipe some 140 m long passing from the southwestern corner of the lake over the lowest freeboard of the moraine and discharging into an existing water course. The discharge flow speed was reported to be about 9 m s⁻¹, giving an approximate discharge of 1401 s⁻¹ (van Nes 1996). The successful installation of this siphon is the first time in the Himalayas that such measures have been used. Having demonstrated that the technology works under the prevalent field conditions, additional
measures are now required to achieve the lowering of the lake water level ultimately by between 15 and 20 m. This is the subject of ongoing political discussions. Given that the ice cores within the moraine are actively melting, it is estimated that, unless the water level can be lowered by 3–5 m by mid-1999, the moraine is still likely to fail catastrophically. For each metre of vertical drawdown achieved, 1–1.5 × 10^6 m^3 of water are removed from the volume available to form a GLOF. If a 4 m drawdown can be achieved by the 1999 monsoon, for example, the total volume of water that could form a GLOF could be reduced by 20%.

Furthermore, such a drawdown will reduce the hydraulic gradient and the hydrostatic pressure head at the moraine dam. Consequently, the onset of a breach through the moraine dam may be delayed sufficiently to permit the installation of more permanent remediation measures, with a final lowering of the lake water level to 15–20 m below its present elevation, assuming sufficient funding is granted in time. However, it is clear that even if the total cost of remediation reaches as much as $8 million over 10 years, this is still significantly less than the potential value of the damage that would result from a catastrophic flood.
The general implications of GLOFs in the Himalayas

To date, the exact number of deaths and the value of damage caused by glacier lake outburst floods in Nepal are not known. However, the frequency with which GLOFs are occurring is increasing (Reynolds Geo-Sciences Ltd 1997), as is the pressure on inward investment in major infrastructure projects, and increasing density of populations within the river valleys in the high Himal. In a nutshell, there are now more people and higher value structures at risk from an increasing number of dangerous glacial lakes. This applies not just to Nepal but across the Himalayas. Indeed, it is also true of the Andes.

It is not sufficient to take a lake-by-lake approach as the implications of a potential major disaster to a country like Nepal are enormous – environmentally, socially, politically and economically. There is a desperate need for an integrated national strategy to deal with GLOFs and related matters such as social and economic development, water resources, infrastructural development, and so on. While external aid can be used to alleviate short-term emergency needs, it is far better to discourage a dependency culture and to develop an indigenous capacity to formulate appropriate responses to such problems. It is pertinent to note that while political obfuscation continues, ice cores within moraines are continuing to melt bringing the likelihood of a major disaster nearer unless appropriate action is taken. For this both the political will and the financial means need to be committed, not just for a short time, but over several decades.

Conclusions

Emergency hazard assessment work undertaken at Tsho Rolpa in 1994 has led to the successful installation of a trial siphon. It is thought that this is the first time that such measures have been taken in the Himalayas. Now that the method has been demonstrated to work under
the prevalent conditions, additional initial measures need to be installed by mid-1999 if the lake is to be remediated successfully.

In both the Himalayas and the Andes, the number and sizes of high-altitude mountain lakes are increasing as glaciers recede. With growing populations and increasing numbers of high-cost infrastructure projects, the risk of a major catastrophic flood will also continue to increase unless appropriate action is taken in time.

In addition to dealing with individual cases on an emergency basis, there is a desperate need for a long-term national strategy to deal with glacier lake outburst flood risks and related problems.

Acknowledgements. I am very grateful to the Water and Energy Commission Secretariat (WECS), Ministry of Water Resources, Kathmandu, Nepal, for the invitation to become involved in this work in 1994. I am also very grateful to them and to the Department of Hydrology and Meteorology, Ministry of Science and Technology, for their ongoing support and generous collaboration. My input has been financed by the Emergency Aid Department of the Department For International Development (formerly the Overseas Development Administration), London. The British Embassy in Kathmandu has also been extremely supportive of this work, and to the Ambassador and his staff, I express my gratitude.

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