PERGAMON

Quaternary International 65/66 (2000) 31–47

An overview of glacial hazards in the Himalayas

Shaun D. Richardson*, John M. Reynolds

Reynolds Geo-Sciences Ltd, The Stables, Waen Farm, Nercwys, Mold, Flintshire CH7 4EW, UK

Abstract

Glaciers and snowfields can form potential hazards in the Himalayas, and in similarly glacierised regions of the world. Some glaciological phenomena can have significant impacts upon society over a short time scale (minutes–days), such as ice/snow avalanches and glacial floods. Other related hazards can be equally serious but less obvious when considered on a much longer time scale (months–years–decades), such as glacier volume fluctuations leading to water resource problems. Only when humans and their activities become vulnerable to glacier-related processes is there considered to be a hazard risk.

As glaciers recede in response to climatic warming, the number and volume of potentially hazardous moraine-dammed lakes in the Himalayas is increasing. These lakes develop behind unstable ice-cored moraines, and have the potential to burst catastrophically, producing devastating Glacial Lake Outburst Floods (GLOFs). Discharge rates of 30,000 $m^3 s^{-1}$ and run-out distances in excess of 200 km have been recorded. Despite the scale of the risk, it is possible to assess and mitigate hazardous lakes successfully. Hazard assessment using satellite images has been effective for remote areas of Bhutan, and remediation techniques successfully developed in the Peruvian Andes are now being deployed for the first time in Nepal.

1. Introduction

The main brief of IGCP415 is to examine the extent and timing of Late Quaternary glaciation in Asia and to assess the impact of glacier fluctuations on the continent's hydrological systems. The retreat of glaciers from their Neoglacial maxima provides an insight into the glaciological and glacial geological processes that affected the area during the Late Quaternary and subsequent glacial episodes. Associated with these processes in the current day is the potential risk posed by glaciers and their products to human activities. Any glacier or glacier-related feature or process that adversely affects human activities, directly or indirectly, can be regarded as a glacial hazard (Reynolds, 1992). This covers a range of processes from avalanches threatening the livelihoods (and lives) of hill farmers, catastrophic glacial lake outbursts destroying vital infrastructure and vulnerable communities, through to glacier recession from climate change resulting in increased storage of water behind unstable moraine dams at high altitude.

Whilst a single glacial hazard event rarely involves as many casualties as a large earthquake or major volcanic eruption, the impact upon susceptible areas and communities can be equally significant. One of the largest known cases of a glacially related debris flow travelled over a hill 150 m high; the debris flow front was still 6 storeys high, 500 m wide and travelled at speeds in excess of 80 kph as it reached the crest of the hill before descending on the town of Yungay in Peru in 1971. Twenty thousand people were killed within 5 min of the initiation of the event at Huascarán, Cordillera Blanca (Lliboutry et al., 1977).

Glacial hazards attract attention for two main reasons: (a) the risk of loss of life; and, (b) the serious threat to costly infrastructures such as hydropower installations, roads, etc. As human activities extend further into the high mountainous regions of the world conflicts with glacial hazards are becoming more apparent. Some 32,000 people have been killed by glacial lake outbursts in Peru this century; hundreds of people and livestock have died in the Himalayas in the last 50 years by being swept away in the catastrophic discharges from lakes high in the mountains. Commercial projects in Asian countries are inadvertently extending into areas prone to glacial hazards in response to increased land use pressures and natural resource exploitation. It has been estimated that the costs associated with the destruction of a mature hydroelectric power plant in Nepal, for instance, could amount to over $500 million. The effects of such a loss of generative power could last for a

* Corresponding author. Tel.: 0044-1352-756-196; fax: 0044-1352-759-359.

E-mail address: rgsl@compuserve.com (S.D. Richardson).

1040-6182/00/$20.00
PII: S1040-6182(99)00035-X

Table 1
Types of glacier, glacial, and related hazards

Category	Hazard event	Description	Time scale
Glacier hazards	Avalanche	Slide or fall of large mass of snow, ice and/or rock	Min
	Glacier outburst	Catastrophic discharge of water under pressure from a glacier	Hours
	Jökulhlaup	Glacier outburst associated with subglacial volcanic activity	Hours–days
	Glacier surge	Rapid increase in rate of glacier flow	Months–years
	Glacier fluctuations	Variations in ice front positions due to climatic change, etc.	Years–decades
Glacial hazards (*as above, plus:*)	Glacial Lake Outburst Floods (GLOFs)	Catastrophic outburst from a proglacial lake, typically moraine dammed	Hours
	Débâcle	Outburst from a proglacial lake (French)	Hours
	Aluvión	Catastrophic flood of liquid mud, irrespective of its cause, generally transporting large boulders (Spanish)	Hours
Related hazards	Lahars	Catastrophic debris flow associated with volcanic activity and snow fields	Hours
	Water resource problems	Water supply shortages, particularly during low flow conditions, associated with wasting glaciers and climate change, etc.	Decades

Table 2
Scale of snow and ice avalanches (Perla, 1980)

Size	Potential effects	Order of magnitude estimates		
		Vertical decent	Volume (m^3)	Frequency of occurrence
Sluffs	Harmless	~ 10 m	1–10	10^4 yr^{-1}
Small	Could bury, injure or kill a human	$10–10^2$ m	$10–10^2$	10^3 yr^{-1}
Medium	Could destroy a timber-frame house or car (localised damage)	10^2 m	$10^3–10^4$	10^2 yr^{-1}
Large	Could destroy a village or forest (general damage)	1 km	$10^5–10^6$	One per decade
Extreme	Could gouge the landscape (widespread damage)	1–5 km	$10^6–10^9$	Two per century

generation or more and a major and highly damaging event could jeopardise the economic development of a country such as Nepal. In severe cases, even the perceived threat from glacial hazards may be sufficient to restrict national investment in rural development. Consequently, this threat is now being addressed at the national planning level within host governments of the Himalayan region (Chhetri, 1999).

The aims of this paper are: (a) to provide an overview of the types of glacial hazards associated with glaciation and deglaciation; (b) to examine the processes of formation and development of potentially hazardous glacial lakes in the Himalayas; and (c) to discuss briefly technical and implementation issues associated with hazard assessment and mitigation, as illustrated by recent case histories from Nepal and Bhutan.

2. Types of glacial hazards

There are two main types of glacial hazard (Table 1). Direct glacial hazards, often referred to as *glacier* hazards, involve the direct action of ice and/or snow and include events such as ice avalanches, glacier outburst floods and glacial advances. Indirect *glacial* hazards arise as a secondary consequence of a glacial feature or process and may include catastrophic breaching of moraine-dammed lakes or water resource problems associated with wasting glaciers and climate change. Human vulnerability must be displayed before any particular glaciological feature is classified as a hazard.

2.1. Snow/ice avalanches

Avalanches are perhaps the most widely known and studied of the glacier and snow related hazards. *Snow avalanches* can be classified according to the volume of material involved in a single event and the amount of its vertical descent as indicated in Table 2. Occurrence intervals are estimated as orders of magnitude only, ranging from 10^4 yr^{-1} for sluffs through to perhaps two extreme snow avalanches per century. Avalanche paths comprise three main parts: the starting zone, the track and the runout-deposition zone. Avalanche style is dependent upon the type of initiation mechanism and starting zone failure patterns and falls into two categories, the

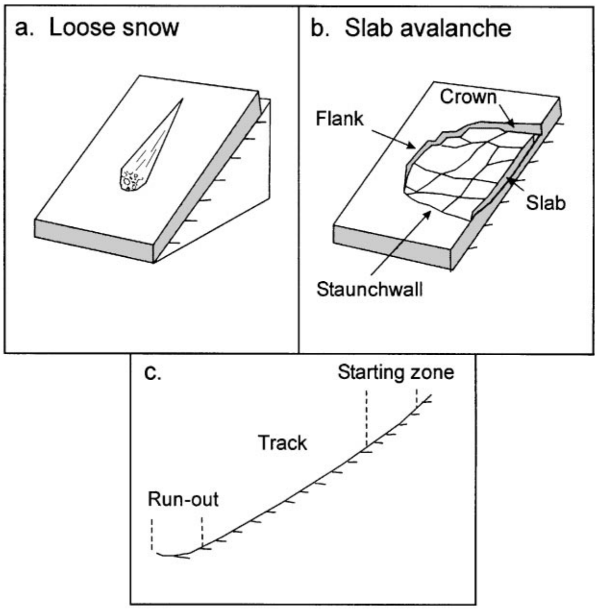

Fig. 1. (a) Loose snow and (b) slab avalanches, with (c) the starting zone, track and run-out zone in profile (Reynolds, 1992).

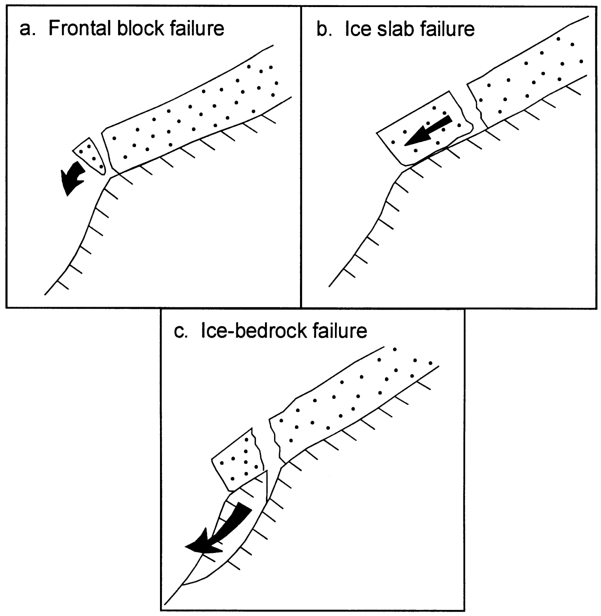

Fig. 2. Three styles of ice avalanches (Perla, 1980).

loose-snow avalanche and the slab avalanche, the latter of which tends to be the more dangerous (Fig. 1).

Snow avalanche forecasting and risk mapping are practiced in western areas including N. America, Scandinavia and Europe. Automated models have been developed that can process input data on factors such as climate, terrain conditions, snow depth and avalanche histories to calculate risk probabilities (Keylock et al., 1999) and to provide a forecast with comparable accuracy to existing public warning systems (Schweizer and Föhn, 1996). No such systems are employed in the high mountainous regions of Central Asia. Regular snow avalanche tracks in the High Himalayan valleys of Nepal, for example, are more likely to be known through past experiences of the local villagers. The vulnerability of the local people to snow avalanches is often reduced by not exploiting the land within known avalanche tracks. Extreme avalanches involving the loss of life and damage to property and infrastructure such as those in the Khumbu area of Nepal in 1996 are considerably more difficult to mitigate. It is possible to forecast the climatic situation that generates the conditions for large avalanches, even if the events themselves cannot be predicted. Heavy snowfall in eastern Nepal is often associated with post-monsoon cyclones in the Bay of Bengal heading north, for example.

Ice avalanches have three principle modes of release: frontal block failure; ice slab failure and ice-bedrock failure (Fig. 2). The cascading of ice directly onto settlements and/or infrastructure can represent a significant primary hazard in areas where human activities impinge upon the upper glaciated valley catchments. Himalayan regions, however, suffer less from the direct impact of ice avalanches than the more heavily populated areas of Scandinavia and central Europe (cf. Röthlisberger, 1977) and casualties are rarely reported. The indirect affects of ice avalanches represent a far greater problem. Large ice avalanches may block river valleys, temporarily damming rivers. Even minor ice avalanches from hanging or calving glaciers can represent a serious secondary hazard risk when they collapse into moraine-dammed glacial lakes. The importance of ice avalanches as triggers of moraine-dammed lake bursts has also been recorded in the Cordillera Blanca, Peru (Lliboutry et al., 1977; Reynolds, 1992; Reynolds et al., 1998), and the Canadian Cordillera (Clague and Evans, 1994).

2.2. Glacier floods

Glacial floodwaters may be released directly from a glacier either sub-, en- or supra-glacially, or from outbursts of ice- and moraine-dammed glacial lakes. The differing initiation mechanisms, coupled with the affect of valley morphology on the floodwaters, ensure that no two floods have identical characteristics.

Glacier outburst and *jökulhlaup* both refer to the rapid discharge of water under pressure from a glacier (Table 1). The Icelandic term jökulhlaup was used initially to describe the type of flood associated with a subglacial volcanic eruption (Thorarinson, 1939) and has since been used as a synonym of glacier outburst. There are three recorded mechanisms by which glacier outbursts occur: the rupture of an internal water pocket, the progressive enlargement of internal drainage channels

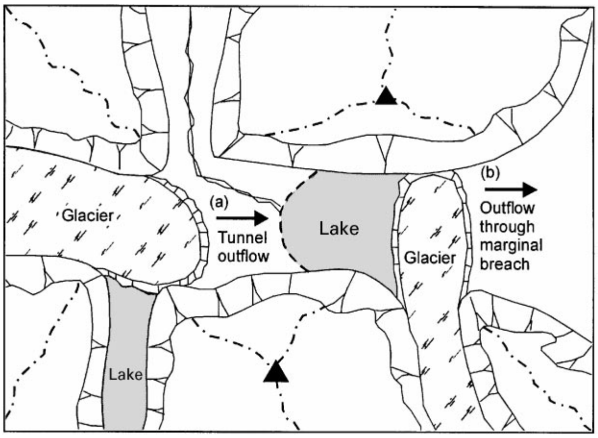

Fig. 3. Two styles of ice-dammed lakes and associated breach mechanisms (Walder and Costa, 1996).

and catastrophic glacier buoyancy, or 'jacking', with sub-glacial discharge. If meltwater within the glacier is able to build up pressure to such a point that the hydrostatic pressure exceeds the constraining cryostatic pressure then a catastrophic burst through the ice may occur. Water may drain into the existing sub-glacial drainage from where it can discharge to the glacier snout. The ensuing flood wave is extremely dangerous as it often develops over a period of just a few minutes leaving little warning for communities downstream (Haeberli, 1983). A link between outburst floods and periods of atypically hot and wet weather in summer and early autumn has been established for floods from South Tahoma Glacier, Mount Rainier, USA (Walder and Dreidger, 1995) and from Bas Glacier d'Arolla, Switzerland (Warburton and Fenn, 1994).

Ice-dammed lakes can drain either by flotation of the ice dam and subglacial discharge, by erosion of an overflow channel into the dam surface, by ice marginal drainage where the glacier dam meets the valley side and/or by mechanical failure of the dam (Fig. 3). Mathematical models have been developed to explain the processes of subglacial and ice-dammed lake drainage through the progressive enlargement of subglacial channels (Nye, 1976; Clarke, 1982). The modelled floods are initiated at the point when the thinnest part of the ice dam becomes buoyant. As water flows beneath the dam, probably in either a single large channel or spread between a number of smaller channels, it may release mechanical and/or thermal energy. The channel(s) are progressively enlarged, allowing an increase in water flow, which leads to further channel enlargement. Drainage is terminated once the cryostatic pressure around the channel becomes greater than the falling water pressure causing rapid channel closure. Consequently, the resulting flood hydrograph typically has a long ascending limb followed by a steep falling limb. The time period over which this process occurs can range from several hours through to days, allowing some time to take preventative measures.

Some inconsistencies between the theory of flotation and progressive channel enlargement with observed flood hydrographs have been recorded. Björnsson (1974, 1976, 1992) noted that jökulhlaups in Iceland often occur when water depths are up to 50 m less than those theoretically required for floatation of the ice dam and that floods often cease more rapidly than their modelled counterparts. Walder and Costa (1996) suggest that ice marginal drainage and mechanical failure tend to produce larger discharge rates than subglacial drainage alone that may account for the modelled underestimates of recorded floods. The rupture of the Hubbard Glacier ice dam, Alaska, in 1986 provides an example of the scale of discharges possible: about 5.4 km^3 of water from Russell Fiord broke through the dam at peak discharge rates up to 105,000 $m^3 s^{-1}$ (Mayo, 1989).

Outbursts from *moraine-dammed lakes* typically occur by lake water overflowing and eroding the moraine dam leading to catastrophic failure once the hydrostatic pressure exceeds the restraining lithostatic pressure. A trigger mechanism such as displacement wave from an ice or rock avalanche, or disintegrating ice-core within the dam is normally required. Processes contributing to the formation and failure of moraine dams are considered in more detail later. Moraine-dammed lake outbursts are known by a variety of terms. *Glacial Lake Outburst Flood* (GLOF) is a term commonly used in the Himalayas to describe the catastrophic bursts from proglacial moraine-dammed lakes. *Débâcle* and *aluvión* are French and Spanish terms, respectively, that are also commonly used in reference to floods from proglacial lakes, although aluvión was originally applied to catastrophic debris flows irrespective of their cause (Lliboutry et al., 1977).

GLOFs in Central Asia have been mainly recorded in the central and eastern Himalayas (Mool, 1995; Yamada, 1998; Reynolds, 1998) and the Qentanglha and Benduan Mountains of south-east Tibet (Ding and Liu, 1992). In contrast the western and north-western margins of the Tibetan Plateau have tended to produce more ice-dammed lake floods and very few GLOFs (Hewitt, 1982; Liu, 1992; Zhang, 1992). GLOFs have also been well documented from the Andes, (Lliboutry et al., 1977; Reynolds, 1992), N. America (Clague and Evans, 1994), and the European Alps (Haeberli, 1983).

2.3. Glacier fluctuations

The direct impact upon society of non-surging glaciers is often considered as one of the 'quieter' natural hazards. Normal glacial advances are characteristically non-catastrophic and it is unlikely for loss of life to be associated with these events. It is the disruption caused by the inundation of land, homes and infrastructure that represents the greatest potential hazard. Whilst communities may be vulnerable to glacial advances, the majority of non-surging glaciers in the Himalayas have been receding during the 20th Century (Mayewski and Jeschke, 1979).

Fluctuations in glacier terminus positions or changes in glacier flow velocities can also produce a variety of indirect hazards. Should a local river be dammed by an extended ice tongue dam, there is a danger of some form of glacial outburst, as previously described. Variations in ice flow velocity can have a destabilising effect on valley-sides and/or terminal moraines and initiate slope failures. MacDonald (1989) reported on the loss of land and property associated with flow changes and erosion at the margins of the Bualtar and Barpu glaciers in the Karakoram Himalaya, Pakistan. Cumulative damage from such high-frequency, low-magnitude events can be as destructive as that created by more catastrophic events, and even greater over a long period of time.

2.4. Glacier surges

Glacier surges are characterised by a sudden increase in ice movement through a glacier by an order of magnitude or more over a relatively short time period, normally weeks to months (Sharp, 1988). A rise in glacier surface elevation and an increase in crevassing typically accompany the surge as the wave of increased ice flow proceeds down glacier. Surges often appear to occur in cycles peculiar to individual glaciers that are not in phase with general climatic trends, complicating attempts to predict their behaviour. Some surges may be contained within the glacier whilst in other cases the glacier terminus may advance several kilometres relative to its pre-surge position. Where a surge reaches the glacier terminus the rapid advance of the snout can lead to problems associated with inundation of land, property and infrastructure (Zhang, 1992). Local rivers or fjords may be temporarily dammed by the advancing glacier tongue, as illustrated by the damming and subsequent outbreak flood of Russell Fiord, Alaska, in 1986 as mentioned above.

The Karakoram Himalaya is believed to contain the highest concentration of surging glaciers outside of the Alaskan–Yukon ranges of North America and the Arctic islands of Svalbard, with 26 reported surges involving 17 glaciers in the last 100 years (Hewitt, 1998). Surging of the Chiring Glacier, north Pakistan, for example, lead to increased crevassing and re-organisation of glacier structure both during and following the surge. Although the surge was contained within the glacier, extensive areas of seracs were created, thus exacerbating the ice avalanche risk. Surging in Himalayan glaciers is still reported infrequently and the total number of glaciers affected, their distribution, and the processes involved are not clearly known.

2.5. Indirect hazards associated with deglaciation

In addition to the hazards outlined above, paraglacial processes associated with deglaciation affect the steep-sided valleys of mountain chains adjacent to the Tibetan Plateau. Glacial and non-glacial stress release from valley sides and the re-organisation of large volumes of unconsolidated sediment during deglaciation provides a ready supply of material to be incorporated into mass movements. Meltwater from glaciers and snow banks combined with freeze–thaw temperature regimes can help to initiate rock avalanches and landslides (Hewitt, 1988). Slope failures can act as a primary hazard by inundating villages and infrastructure directly or form secondary hazards by blocking rivers. In 1841 a flood from a rockslide-dammed lake on the Indus river, to the north-east side of Nanga Parbat, Pakistan, destroyed a Sikh Army camp at Attock more than 200 km downstream. In 1858 the breach of a landslide across the Hunza valley caused a 9 m rise of river level at Attock in less than 10 h (Owen, 1995). Sarez Lake, in the Pamir Mountains of Tajikistan, is currently attracting attention in the popular scientific press (Pearce, 1999). The lake, which is 60 km long and up to 500 m deep, was dammed by a landslide in 1911 but is now showing increasing signs of instability. Five million people throughout four countries could be affected should the dam burst catastrophically.

3. Glacial Lake Outburst Floods in the Himalayas

Glacial Lake Outburst Floods are one of the most catastrophic and dominant processes to modify Himalayan valleys during deglaciation. Discharge rates from breached moraine dams can easily attain 30,000 $m^3 s^{-1}$ and drain volumes in excess of 50 million m^3 of water. Large amounts of sediment are transported by the high discharge rates. One historical event in the Seti Khola river basin, Nepal, in ca. 1555 inundated 450 km^2 of the Pokhara basin with up to 50–60 m thickness of debris. The affects from a large GLOF can impact on the lower reaches of valley systems many kilometres from the source lake. In 1994 a catastrophic flood from Luggye Tsho glacial lake, northern Bhutan, produced a flood wave that still reached a height of over 2 m at a distance of more than 200 km from the source.

3.1. Recorded GLOFs in the Himalayas

On 4 August 1985, after a particularly warm period in July, the terminus of Langmoche glacier in the Dudh Kosi river basin of Nepal collapsed into Dig Tsho glacial lake. The resulting displacement wave travelled along the lake, overtopped the lake's moraine dam and initiated a period of accelerated erosion that ultimately led to dam

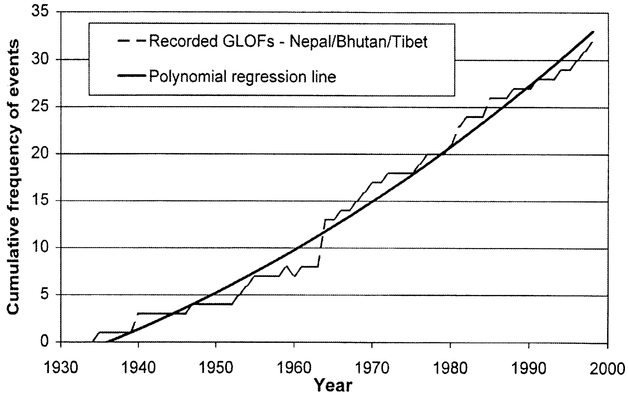

Fig. 4. Cumulative frequency of recorded glacial lake outburst floods in Central Asia.

failure. Initial discharge rates of the ensuing flood may have been as high as 2000 $m^3 s^{-1}$, with an average discharge of 500 $m^3 s^{-1}$ over 4 h, draining a total volume of 6–10 million m^3 of water (Vuichard and Zimmermann, 1986, 1987). Five people were killed and a small run-of-river hydropower scheme was completely destroyed shortly prior to its commissioning. Environmental degradation was severe with the loss of cultivated land and destabilisation of valley sides and river channels for 90 km downstream.

The Dig Tsho flood of 1985 stimulated glacial hazards research in the Himalayas, particularly into floods from moraine-dammed lakes. From work published in the aftermath of the flood it soon became apparent that little was known about the problem, both in terms of recognising and assessing potential hazards and predicting flood behaviour. Partial glacier inventories and information on glacier fluctuations are available for many Himalayan regions (Mayewski and Jeschke, 1979; Fushimi and Ohata, 1980; Higuchi et al., 1980; Shiraiwa and Yamada, 1991; Yamada et al., 1992). None of these includes information on glacial lakes. A joint Sino-Nepalese field investigation in 1988 produced an inventory of glaciers and glacial lakes in the Arun and Bhote Koshi basins in Nepal and Tibet (Liu and Sharma, 1988). Despite the increased interest in glacial lakes and their floods, published work still concentrates on historical accounts of past events and preliminary identification of glacial lakes (Ives, 1986; Vuichard and Zimmerman, 1987; Yongjian and Jingshi, 1992; Yamada, 1993; Mool, 1995). Only rarely are glacial hazards assessed in detail by considering the glaciological and geological processes involved (Reynolds, 1998).

One of the fundamental problems facing Himalayan regions is that the potential threat from glacial hazards is not defined. Historical records compiled by the authors of 33 Himalayan GLOFs indicate that the frequency of events appears to be increasing (Fig. 4). It is also known that many existing lakes are growing in size as glaciers retreat and their moraine dams degrade (Reynolds, 1998; Yamada, 1998). The potential for larger and more frequent floods is undoubtedly increasing (Reynolds, 1999b). In the Himalayas, as throughout Central Asia generally, the number of potentially dangerous lakes and the number of glaciers that may develop these lakes in time remain unknown.

3.2. Development of potentially dangerous glacial lakes

Moraine-dammed lakes generally form by meltwater collecting behind moraines abandoned on the glacier foreland, and/or by the coalescence of supraglacial ponds to form large lakes dammed by debris-covered stagnant glacier ice. One of the most important controls on the initiation of lake development is glacier style. Long valley glaciers can respond to negative mass balances by thinning whilst maintaining a relatively stable terminus position. Supraglacial melt may collect on the glacier surface to form small melt ponds in the first instance. If glacier structure impedes drainage of the individual ponds, they can coalesce to form large lakes. Some of the largest glacial lakes in Nepal, Tibet and Bhutan have formed in this manner. Examples include Tsho Rolpa (3.2 km long), Thulagi (2 km long), and Imja (1.3 km long) lakes in Nepal, and Luggye Tsho (1.8 km long) in Bhutan. Smaller lakes are typically associated with shorter and steeper glaciers. A steep surface gradient facilitates drainage of water from the glacier surface to proglacial positions where it collects behind terminal moraine ridges. As terminal moraines from the Neoglacial maxima often exceed 100 m in height the resulting lakes can still contain 1–20 million m^3 of water, representing a serious hazard threat. Steep retreating glaciers are also prone to avalanching and can collapse into the lake initiating a catastrophic dam burst. The above models are not exclusive, as individual lakes will develop according to the local glaciological and geological conditions. Thulagi lake in the Upper Marsyangdi catchment, northern Nepal, for example, is dammed by a debris covered stagnant ice body some 100 m thick that pre-dates the last glacial advance (Hanisch et al., 1998, 1999; Pant and Reynolds, 1999).

Lakes of a size large enough to represent a significant hazard risk to communities and developments down-valley can develop very quickly, often over a period of a few years. In many occasions the first time the existence of a lake becomes apparent is when it floods communities down-stream. Investigation of the processes and rates of lake development is often retrospective. Average growth rates for Tsho Rolpa, Imja, Lower Barun and Thulagi lakes in Nepal, for instance, have been calculated from maps, aerial photographs and satellite images (Yamada, 1998). All of these lakes formed within the last 30–45 years, expanding in length by an average 33–71 m yr^{-1} and in depth by ca. 3 m yr^{-1}. Potentially

Fig. 5. Steep calving glacier terminus at Thulagi, Nepal. Crevasses immediately behind the ice cliff and undercutting at the water line accelerate calving processes.

dangerous lakes can develop far more quickly. At Hualcán in the Cordillera Blanca, Peru, a dangerous lake developed in only 5 yr between 1988 and 1993 whilst the local glacier retreated to a hanging position above the lake. Emergency remediation was successfully completed in order to safeguard the lives of 25,000 people at Carhuaz, the main town down-valley of the lake (Reynolds et al., 1998).

Routine monitoring of lakes in their early stages of development, or proto-lakes, is rarely undertaken and the processes by which lakes develop have not been directly recorded in the Himalayas. The distribution of transient supraglacial ponds and their drainage has been related to glacier structures (RGSL, 1999). Glacier structure has also been invoked as a controlling mechanism on the spatial distribution and development of supraglacial lakes and drainage in other glacial environments (Hambrey, 1977; Reynolds, 1981). At a certain threshold in the lake's evolution the active snout of the glacier migrates from its original position at the terminal moraine to the up-glacier side of the lake. The rejuvenated ice front often forms a steep ice cliff that calves into the lake, accelerated by undercutting at the water line (Fig. 5). Small active ice cliffs are frequently seen on the proximal side of supraglacial ponds, indicating that this process may occur relatively early. Once established, glacial lakes typically expand by ice melt and thinning of the moraine dam and by a combination of ablation and calving of the glacier at the proximal end of the lake.

Calving of glaciers into glacial lakes increases the lake area and generates displacement waves in the process. Floating ice tongues are considered to be highly dangerous. They can collapse catastrophically into the lake through Reeh calving processes or due to inappropriate remediation efforts to lower the lake (Lliboutry et al., 1977). Grounded ice cliffs are most typical in the Himalayas but still have the potential to produce displacement waves sufficiently large to overtop and rupture moraine dams. Calving processes at freshwater termini have received little empirical study. The main mechanisms of calving appear to be by undercutting caused by waterline melting and spalling, by exploitation of crevasses, and occasionally by subaqueous calving of a submerged ice foot (Warren et al., 1995; Kirkbride and Warren, 1997).

Thermokarst processes have long been recognised as a mechanism for de-icing ice-cored moraines (Clayton, 1964; Healy, 1975). Wastage of ice-cores increases the volume of the lake and poses a serious risk to dam stability. Average rates of subsidence due to melting of

Fig. 6. Exposed ice core in the end moraine dam at Tsho Rolpa, Nepal. An ice block is failing along a well-developed fracture, interpreted as a relict crevasse, that lies behind and parallel to the cliff edge at the location of the persons (circled).

buried ice in the moraine dam at Imja, Nepal, have been measured at up to 2.7 m yr^{-1}, changing the lake shoreline position and diverting drainage from the lake (Watanabe et al., 1995). Repeat observations at Tsho Rolpa, Nepal, have identified that the affects of melting ice cores are spatially and temporally variable (Reynolds, 1999a). At one location on the terminal moraine a sinkhole identified in 1995 developed into a small ice cliff 2 m high in November 1996. By September 1997 it was found that the exposed ice cliff had increased in height to 19 m and the melt pond at the foot of the ice cliff had deepened to over 5 m. These periods of accelerated melting appear to be controlled by relict glacier structures, particularly crevasses, within the stagnant ice body (Fig. 6).

3.3. Failure of moraine-dammed glacial lakes

The factors contributing to the overall hazard risk from glacial lakes are shown in Fig. 7. The hazard risk is considered to be high if the lake displays certain characteristics or thresholds to failure. First, the size of the lake influences the amount of water available for a GLOF. The width of the dam relative to lake depth determines the hydrostatic pressure on the dam and local hydraulic gradients. Narrow dams and those with little freeboard between the lake level and the top of the dam are more vulnerable to overtopping and erosion by displacement waves from rock/ice avalanches. The presence of melting buried ice within the dam can reduce the height of the freeboard. Ice-cores also provide potential pathways for lake water and ice melt to percolate through moraines thereby undermining dam integrity. The hazard risk for a particular lake will be defined by the combination of these thresholds of lake volume, dam width, freeboard height and buried ice-cores combined with evidence of human vulnerability.

Potentially dangerous lakes typically require a trigger mechanism to initiate a flood (Fig. 7). From historical records compiled by the authors, the failure mechanisms and timing are known for 26 GLOFs in the Himalayas this Century. Over 53% of these were initiated by displacement waves from ice avalanches that collapsed into the lakes from hanging or calving glaciers (Fig. 8). For over 23% of reported GLOFs the cause of the flood remains unknown, whilst moraine collapse due to seepage (12%), displacement waves from rock avalanches (8%) and collapse of moraines due to melting ice-cores (4%) account for the remainder of recorded events. Further trigger mechanisms can include settlement and/or

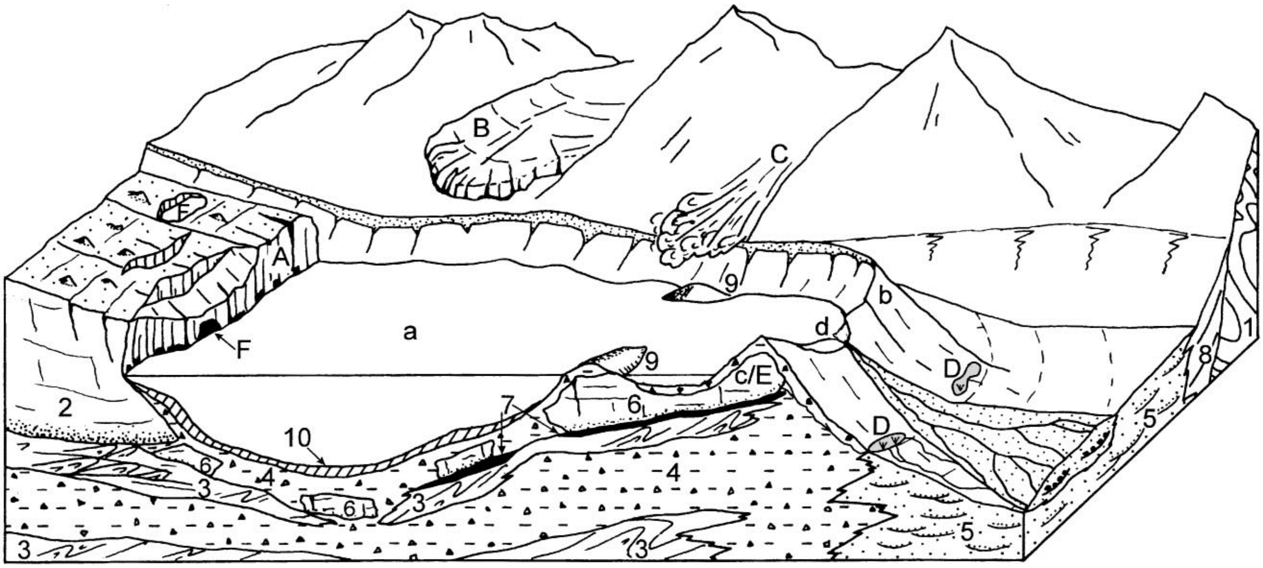

Fig. 7. Schematic diagram of a hazardous moraine-dammed glacial lake. Geological successions include (1) bedrock; (2) receding glacier; (3) stacked subglacial tills and (4) supraglacial tills representing multiple glacial advances; (5) complex interbedded glaciofluvial sediments, supraglacial tills and gravity flow diamicts in terminal and lateral moraine ridges; (6) stagnant glacier ice with (7) basal melt-out till; (8) valley-side fan deposits; (9) hummocky moraine resulting from melt of ice-cores (thermokarst); and (10) lake sediments. Factors contributing to the hazard risk include (a) large lake volume, (b) narrow and high moraine dam, (c) stagnant glacier ice within the dam, (d) limited freeboard between the lake level and crest of the moraine ridge. Potential outburst flood triggers include avalanche displacement waves from (A) calving glaciers, (B) hanging glaciers, and (C) rock falls; (D) settlement and/or piping within the dam (due to progressive seepage or seismic activity); (E) melting ice-core; (F) catastrophic glacial drainage into the lake from sub- or en-glacial channels or supraglacial lakes.

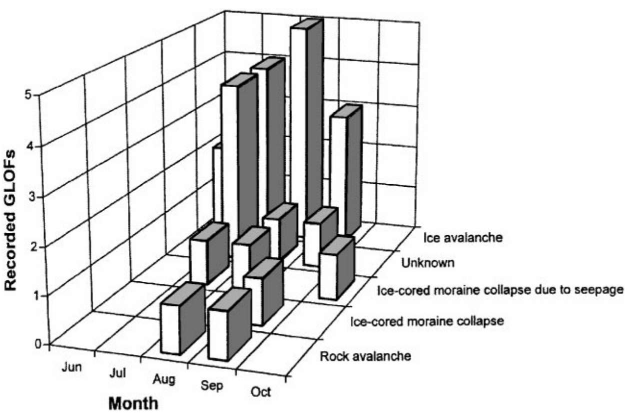

Fig. 8. Causes and monthly distribution of recorded glacial lake outburst floods in Central Asia. Sample number = 26.

piping within the moraine as a result of earthquake shocks, sudden glacial or meteoric drainage into the lake, and inappropriate engineering works during remediation (Reynolds, 1992). All of the above-mentioned GLOFs occurred between June and October (Fig. 8). Lake levels at this time are at their highest due to increased summer ablation from glaciers and the influence of the monsoon rains between June and September. Calving rates from glaciers typically tend to increase in the ablation season. The highest rates of ice melt within moraines would also be expected during this period. However, the most rapid disintegration of the ice-cored moraine at Tsho Rolpa occurred between October 1996 and May 1997 when average daily air temperatures reach their lowest of ca. −9 to −12°C (Yamada, 1998). Thermokarst development in this case appears to have been influenced more by the local ground conditions, particularly the exploitation of relict glacier structure, than by climate.

3.4. GLOF characteristics

The style of floods from natural dams is controlled by the lake volume, the height, width, and composition of the moraine dam, valley morphology and vegetation, and sediment availability within the dam and downstream. Empirical relationships between dam height, lake volumes and the potential energy of reservoir waters have been obtained from documented outbursts from constructed dams, landslide dams and ice dams (Costa, 1988; Costa and Schuster, 1988; Björnsson, 1992). There is less documentation on floods from moraine-dammed lakes, particularly in the Himalayas, largely because few floods have been successfully recorded. One exception is the flood that emanated from Luggye Tsho in Bhutan in October 1994 for which a complete hydrograph from 100 km downstream of the lake is available (Fig. 9). Another hydrograph 200 km from the source lake began to record the steep rising limb of the flood but the recording instruments were destroyed once the flood wave reached 2 m in amplitude.

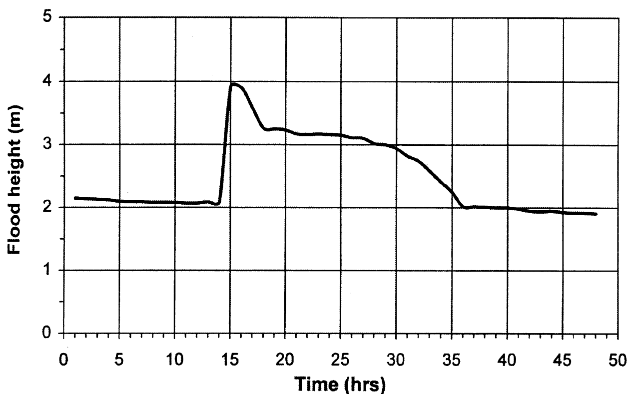

Fig. 9. Flood hydrograph at Kerabari for the GLOF from Luggye Tsho, Bhutan, in October 1994. The recording station lies approximately 100 km from the source of the flood.

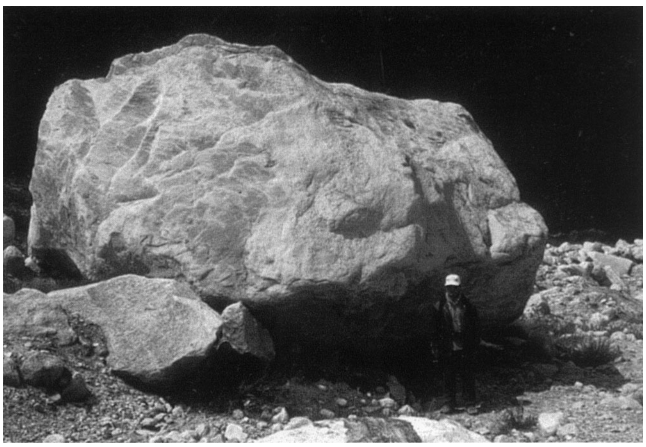

Fig. 10. A transported clast on the surface of the debris fan deposits produced by a GLOF from Chubung Lake, Rolwaling Himal, Nepal, in 1991. The mass of the clast is estimated at 200 tonnes.

Clague and Evans (1994) compared the peak discharges from natural dams in the Canadian Cordillera. They found that for a given amount of potential energy (a function of lake volume, dam height, and the specific gravity of water) moraine-dammed lakes produced floods of higher discharges than landslide or glacier dams. The initial burst through the moraine is often explosive and can propel boulders of the order of 200 tonnes at right angles from the breach for up to a few hundred metres (Fig. 10). Characteristic debris fans containing poorly sorted coarse debris form adjacent to the breach (Fig. 11). Sediment and vegetation are incorporated into the flood as it continues down-valley, often producing debris flow characteristics. Local eyewitnesses to the 1995 Dig Tsho GLOF in Nepal, for example, reported that "the surge front appeared to move down-valley rather slowly as a huge black mass of water full of debris [*and that*] trees and large boulders were dragged along [*and*] some of the trees were in upright positions" (Ives, 1986).

Occasionally, flood deposits are well preserved in the geological record. Coxon et al. (1996) reconstructed a Late Quaternary flood from a former ice-dammed lake in the Lahul Himalaya, northern India, from geomorphological and sedimentological studies. Peak discharges of between 21,000 and 27,000 $m^3 s^{-1}$ were calculated with about 1.5 km^3 of water draining from the lake. More typically, flood deposits are reworked rapidly, making the identification of former events very difficult unless direct links with former shorelines or breached moraines can be proven.

4. Glacial hazard assessment and mitigation

There are three phases of glacial hazard management: (i) identification of the potential hazard; (ii) monitoring and assessment of potential hazards; and (iii) development and implementation of a remediation plan (Reynolds and Richardson, 1999). Assuming that the first two have been undertaken comprehensively, then the remediation plan can be extremely effective. This may be a multi-phase programme over a significant number of years. It is not unusual for the time taken from identification of a potential hazard through to final remediation to be of the order of ten years.

Assessment and remediation plans for glacial lakes in the Himalayas (Rana et al., 1999) have been developed from experience in the Peruvian Andes (Lliboutry et al., 1977; Reynolds et al., 1998). The common methods of remediation are: (i) initial siphoning; (ii) excavation of spillways; (iii) tunnelling; or (iv) a combination of these methods. Rarely explosives have been used to blast new channels but this is a desperate action taken only as a last resort. It is not recommended. The following case histories illustrate examples of glacial hazard assessment and mitigation techniques applied in Bhutan and Nepal.

4.1. *Glacial hazard assessment in Bhutan*

During a commission to investigate the glacial hazards associated with a particular river catchment in central Bhutan in October 1998, a nationwide overview of all the country's glaciers was also undertaken. This was made possible by access to 1 : 50,000 prints of SPOT imagery from 1989 and 1990 made available by the United Nations. Over 300 glaciers were examined in detail from the satellite images and geohazard assessments were undertaken on 154 glaciers. Given that much of northern Bhutan is still regarded as terra incognito due to its extreme remoteness, the only practical methods of initial assessment of these environs is by remote sensing.

Of considerable concern to the Bhutanese authorities is the area known as Lunana at the head of the Pho Chhu

Fig. 11. Typical residual debris fan produced by catastrophic failure of moraine-dammed lakes. This breach of Artesancocha lake in the Peruvian Andes was caused by an ice avalanche from the ice cliff of Artesanraju, clearly visible behind the drained lake.

river in west central Bhutan. On 7th October 1994, Luggye Tsho burst through its southern lateral moraine and discharged approximately 48×10^6 m^3 of water into the Pho Chhu river. The ensuing Glacier Lake Outburst Flood travelled rapidly downstream causing significant damage and resulting in 23 deaths. The Dzong at Punakha, the former seat of the Bhutanese Government until 1952, was badly damaged in the flood. Even though Punakha is 84 km from the source of the flood, its magnitude was still sufficient to cause major damage here and was the main location at which fatalities occurred. The flood hydrograph from a station about 16 km further downstream from Punakha is shown in Fig. 9.

Luggye Tsho is one of a number of glacial lakes that are linked integrally together in a complex (Fig. 12). Initially concern over the stability of Lunana Lake (later called Raphstreng Tsho) was raised by local inhabitants in the late 1970s. The Bhutanese Government, largely through the cooperation of the Indian Government, undertook two initial field investigations into the state of the Lunana Lake/Raphstreng Tsho in 1984 and 1986 (Sharma et al., 1987). However, these investigations concentrated on just Lunana Lake/Raphstreng Tsho and did not place this glacial system into an appropriate geohazard context. The conclusion was that the lake was not in any imminent danger of bursting. The lake that burst was one that was not investigated.

After the disastrous 1994 outburst flood from Luggye Tsho, another field investigation was undertaken (Bhargava, 1995) by the Geological Survey of India in collaboration with the Geological Survey of Bhutan. However, their main emphasis was on the metamorphic geology of the area and on collecting herbs for the then Indian Ambassador to Bhutan; hardly an applicable approach to glacial hazard assessment. Remediation measures were recommended that did not take into consideration the effects of other immediately adjacent lakes and glaciers, e.g. Thorthormi Glacier (Fig. 12).

The field investigations undertaken to date in the Lunana area have not fully utilised nor appropriately integrated the information available from satellite imagery and other sources. It is clear from the images available that Thorthormi Glacier is undergoing rapid degradation (Leber et al., 1999) with the consequential development of a major glacial lake. This is dammed from Raphstreng Tsho by a 65-m high and highly unstable moraine dam. The current remediation, which involves reducing the lake level within Raphstreng Tsho by

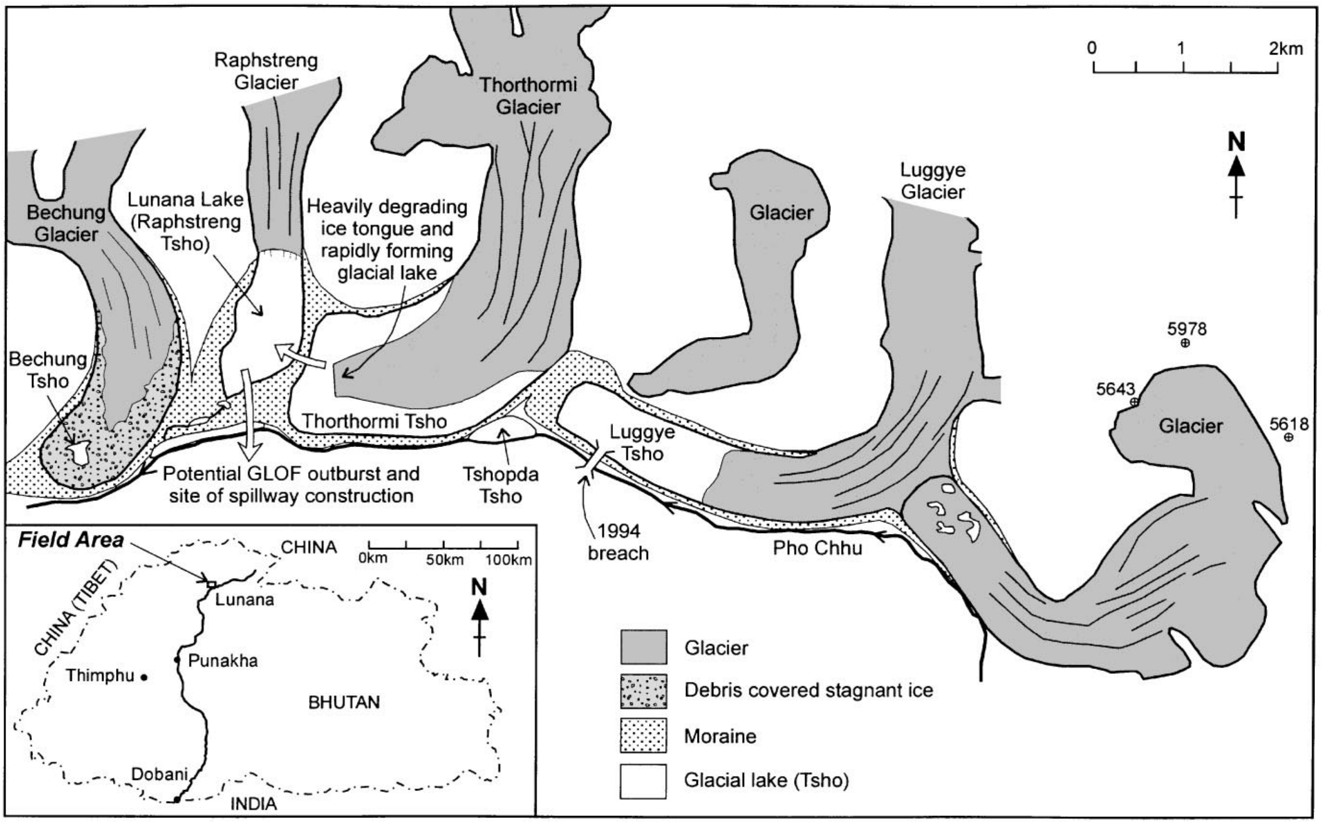

Fig. 12. Schematic relationship between glaciers and glacial lakes in the Lunana area of northern Bhutan. The locations of the Luggye Tsho breach in October 1994 and of the feared potential flood due to existing remediation measures are indicated.

manually excavating a channel using 200–500 labourers, appears not to take into account the effect that this will have on the dividing moraine dam. It is feared that the current remediation may induce the failure of the moraine dam between the two lakes leading to a catastrophic glacier outburst flood, initially from Thorthormi Glacier lake into and thence from Raphstreng Tsho. The combined volume of these two lakes is estimated at 120×10^6 m^3. The burst of 48×10^6 m^3 of water from Luggye Tsho in 1994 travelled for over 200 km and even at this distance the flood wave was estimated at over 2 m high, as discussed previously. A combined flood with potentially twice the volume of that from Luggye Tsho would be even more devastating and would undoubtedly travel into and cause damage in northern India. The main east-west road from Shiliburi to Guwahati in India could be adversely affected.

The overview of Bhutanese glaciers also led to the identification of a number of other potentially dangerous glacial lakes. The relevant authorities have been informed but it is expected that little if anything will be done to mitigate these potential outburst floods largely through the lack of available funds. Unfortunately, funds for disaster relief are often easier to obtain than financial support for hazard mitigation and disaster preparedness.

The above example clearly shows the benefit of using high quality remote sensing imagery as part of the available data on which to base a remediation strategy. No matter how detailed the field work that is undertaken, it has to be information that is pertinent to the geohazard problem. The investigations undertaken (e.g. Sharma et al., 1986; Bhargava, 1995) are inconclusive due to concentrating on those issues that were of interest to the available field team rather than on gathering the correct information for sound decision making for subsequent remediation works. This example also demonstrates the importance of engaging those with the relevant experience and expertise. This was actually recommended in 1994 by a Bhutanese field team (Tashi et al., 1994) that went to the field only a week after the disaster. However, their advice has not been followed in any subsequent investigation in the Lunana area.

4.2. Glacial hazard assessment and mitigation at Tsho Rolpa, Nepal

Tsho Rolpa lies at an altitude of 4450 m a.s.l. about 110 km north-east of Kathmandu at the eastern end of the Rolwaling Valley (Fig. 13). The lake is about 3.5 km long × 0.5 km wide and at least 135 m deep at its deepest

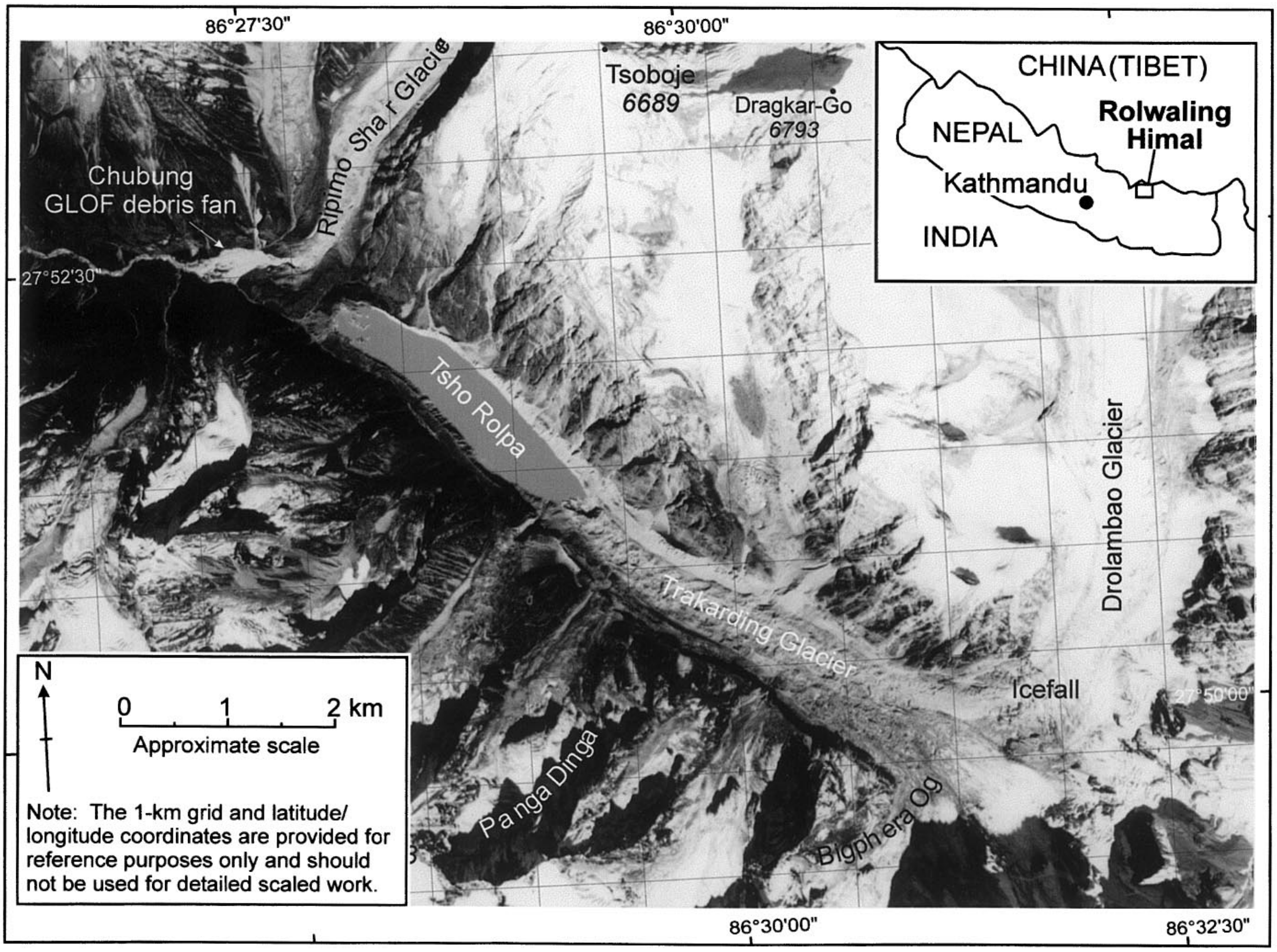

Fig. 13. Aerial photograph of Tsho Rolpa glacial lake and Trakarding Glacier in the Rolwaling Valley, Nepal. A debris fan produced by a GLOF from the adjacent Chubung lake in 1991 is visible to the west of Tsho Rolpa.

point. It is fed by Trakarding Glacier to the south-east (Fig. 14a), which is itself a composite glacier supplied by three glaciers from among the peaks to the east and south east of Tsoboje (6689 m). The north-western end of the lake is dammed by a Neoglacial moraine complex that is up to 150 m high and is partly cored by stagnant glacier ice (Fig. 14b). The lake currently holds about 110×10^6 m^3 of water; it is thought that a Glacier Lake Outburst Flood could occur at some time in the near future with a potential volume of up to 35×10^6 m^3 of water. Several villages in the Rolwaling Valley and the construction site for a water intake for a new hydro-electric power (HEP) scheme at Khimti, 80 km down-stream from Tsho Rolpa, are at risk from a possible GLOF. More details of the background to this project have been given by Rana et al. (1999) and by Reynolds (1998, 1999a).

One of the present authors (JMR) received an invitation in 1993 to help with the problem at Tsho Rolpa from the Water and Energy Commission Secretariat (WECS), Ministry of Water Resources, His Majesty's Government of Nepal, Kathmandu. Although WECS had undertaken some preliminary observations in the Rolwaling valley and around Tsho Rolpa in 1993 in association with some Japanese researchers (Mool 1995; Yamada 1993), little was known about the potential hazard risk. Field assessments of the moraine dam and Trakarding Glacier have subsequently been undertaken in November 1994, May/June 1997, October 1997, and May/June 1999. An extensive library of ground photographs has been compiled for the analysis of relative rates of geomorphic change within the moraine ridge and at the ice front. Photographs, geomorphological mapping and basic field measurements have been used to record the key thermokarst processes that contribute to moraine degradation (Reynolds, 1999a). To determine the extent and thickness of buried ice within the moraine and under the lake a detailed Ground Penetrating Radar survey has been completed. At the time of writing interpretation of the radar data is ongoing. In addition, an analysis of

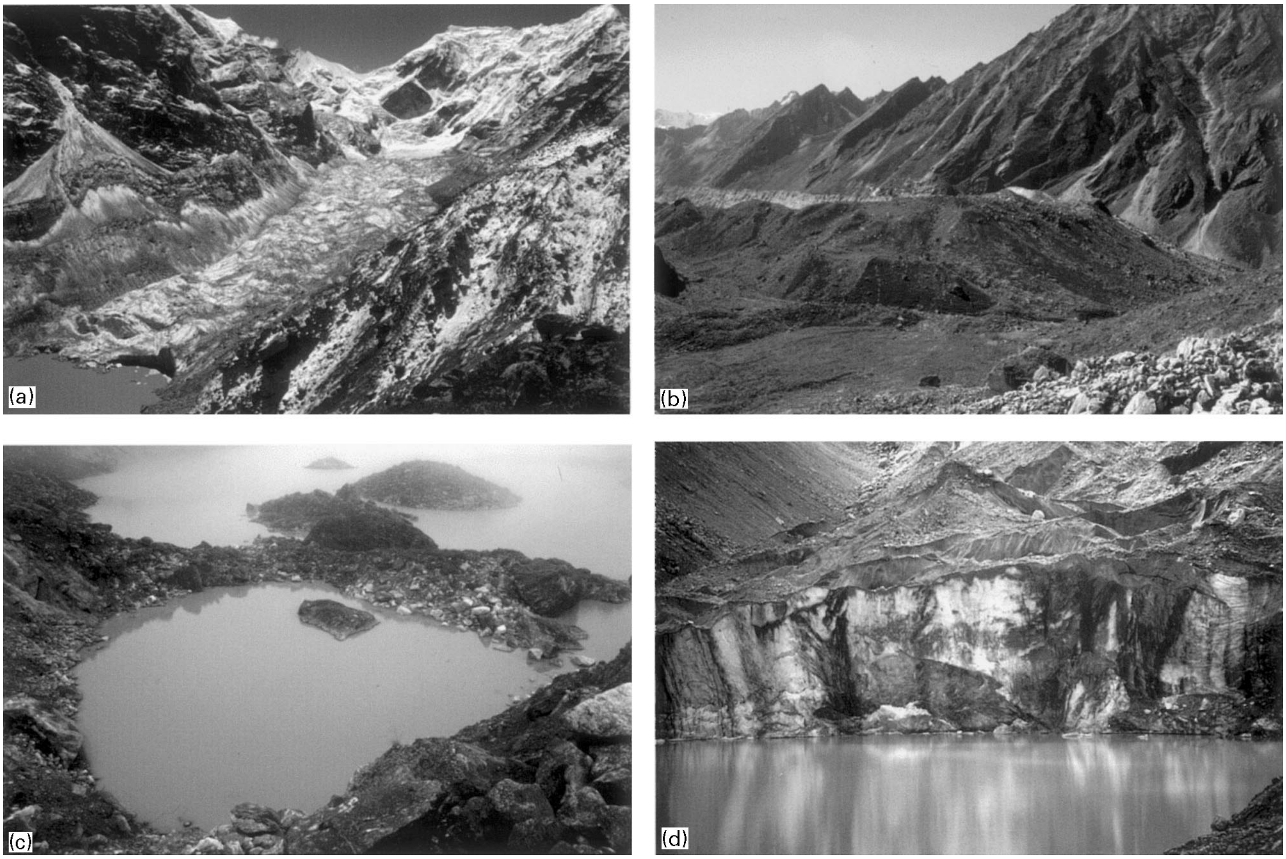

Fig. 14. Glacial lake formation and hazard assessment at Tsho Rolpa, Nepal. (a) The debris covered composite Trakarding Glacier, (b) the 150 m high end moraine dam, (c) thermokarst topography on the proximal side of the end moraine ridge, and (d) detail of Trakarding Glacier ice cliff showing the fractured and partially undercut cliff face that threatens to produce displacement waves.

structures within the Trakarding Glacier has been undertaken from vertical aerial photographs acquired in 1992 and from oblique aerial photographs obtained during a helicopter overflight in October 1998 (RGSL, 1999).

Tsho Rolpa formed by the coalescence of supra-glacial ponds on the stagnating Trakarding Glacier. The earliest evidence of lake development is recorded on a Survey of India mapsheet at 1 : 50,000 scale, compiled from aerial photographs in 1957–1959 (Mool et al., 1993). Tsho Rolpa at this time had an area of ca. 0.23 km^2, comprising one larger lake and several small ponds. By 1993 the lake had increased to ca. 3.2 long with an area of ca. 1.37 km^2. Many criteria indicative of a potentially dangerous glacial lake are evident at Tsho Rolpa. Initial field investigation in 1994 identified at least two areas of hummocky moraine within the main moraine ridge that were interpreted as being ice-cored (Reynolds, 1998, 1999a). Both of these areas have shown evidence of continued degradation. At the north-western end of the moraine melting is particularly dominant, with average subsidence rates estimated in excess of ca. 2 m yr^{-1}. The presence of buried ice in the terminal moraine was confirmed in May 1997 by the exposure of an ice cliff up to 11 m high (Fig. 14c). Preliminary interpretation of the radar data suggests that ice possibly extends to the rim of the moraine and to depths well below current lake level. Melting of the ice poses a serious hazard risk. Not only will the dam freeboard be reduced making it more vulnerable to displacement waves, but also fractures in the ice could provide pathways for lake water to penetrate to the edge of the moraine. If the hydrostatic pressure becomes greater than the lithostatic restraining pressure of the dam, an explosive failure could occur. Observed seepage on the distal flank of the moraine ridge is a further threat to the structural integrity of the dam. Chemical analysis of the spring water suggests that the lake is the source of the seepage, rather than meltwater from the ice-core (Yamada, 1998). The water pathway through the moraine is not known at present and remains a cause for concern.

Ice avalanche activity from Trakarding Glacier terminus is a further potential trigger mechanism for a GLOF. Displacement waves, caused by ice avalanches from the ice cliff, have the potential to overtop the moraine leading to regressive erosion and moraine failure. The largest waves observed to date occurred in 1997 with amplitudes between 1.3 and 2 m at the terminal moraine. The ice cliff at this time was ca. 40–60 m high, undercut, and steep across its whole width (Fig. 14d). Waves of this size have so far presented more of a threat to the safety of personnel on-site than to the stability of the moraine. However, as the Trakarding Glacier has retreated its ice cliff has generally become higher resulting in greater avalanche magnitudes since 1994. Consequently, the risk due to waves overtopping the moraine dam and causing regressive erosion on the distal side is also increasing with time.

In response to the hazard assessment in 1994, Wavin Overseas B.V., Holland, funded and installed a trial siphon over part of the north-western terminal moraine in May 1995. This consisted of a triple-inlet pipe from the lake connecting to a single pipe (all 160 mm O.D.) whose discharge outlet was located about 80 m down the outer flank of the moraine. Siphons have been used successfully to partially drain lakes in the Peruvian Andes at comparable altitudes (Reynolds et al., 1998), and were considered to be the ideal first step in a remediation plan. Once the technology had been proved, a proposal for the phased remediation of Tsho Rolpa was prepared on behalf of His Majesty's Government of Nepal in March 1996. Phase I was to comprise an initial lowering of the lake by 3 m using siphons to provide respite from the immediate hazard threat and to reduce the total amount of water available to form a flood. The second phase was to involve cutting a channel through the moraine to achieve a draw-down of 20 m, which would have increased the width of the terminal moraine dam to up to 500 m.

The remediation strategy was amended following delays in the funding agreement procedure between the Dutch Government and His Majesty's Government of Nepal (HMG/N). Given the rapid rate of deterioration of the moraine dam by May 1997, HMG/N introduced emergency strategic measures in June 1997 to provide a manual early warning system for the local villagers and the Khimti hydro-power installation. Army personnel were deployed at the moraine and downstream at Na to provide warnings by radio to Kathmandu if needed. In May 1998, a series of remote sensors was installed along the Rolwaling Khola as part of an Early Warning System funded by the World Bank. The sensors were placed so that if a flood wave of a certain height was recorded by a specific number of sensors, sirens would sound in the villages downstream to alert the local inhabitants. Meanwhile, a revised proposal for remediation of Tsho Rolpa was submitted by His Majesty's Government of Nepal to the Dutch Government in December 1997. Funding worth $2.9 million was granted in March 1998 to implement a remediation programme for estimated completion by June 2000. This will involve the construction of a 4-m deep artificial spillway to lower the lake level by 3–4 m. Mobilisation of the contractors to site and preparation work began in April 1999. The condition of the moraine dam and Trakarding Glacier terminus is being monitored throughout the construction period to ensure that the hazard risk is not exacerbated. As originally planned, an additional phase of remediation, currently under negotiation, will be needed to lower the lake by 15–20 m below its present level before the potential hazard can be considered to have been successfully remediated.

5. Conclusions

Glacier hazards and related phenomena constitute major hazards in the Himalayas and other mountain chains bordering the Tibetan Plateau. The most significant glacial hazards relate to the catastrophic drainage of glacial lakes. The styles of glacial lake appear to be influenced strongly by geographical location. Ice-dammed lakes are typically more common in the west of the region (e.g. Karakoram Himalaya), whilst moraine-dammed lakes dominate in Nepal and Bhutan in the eastern Himalayas. Glacial lake outburst floods from the mechanical failure of moraine-dammed lakes can attain peak discharges of 30,000 $m^3 s^{-1}$, remobilising vast quantities of sediment and causing significant geomorphic change. They destroy property, land, vital infrastructure, and economic developments such as hydropower stations in addition to threatening the lives and livelihoods of the local population. The effects of historical GLOFs have been significant at distances of more than 200 km from the respective source lakes.

Successful hazard assessment depends on an understanding of the processes of moraine-dammed lake formation and failure, coupled with appropriate investigation techniques in glaciology and glacial geology. Remote sensing mapping techniques are particularly valuable for investigating inaccessible glaciers and their lakes. These enable preliminary assessments to be undertaken on a catchment-wide scale more cheaply and quickly than is possible with traditional field investigations. Hazard assessment undertaken by those with insufficient relevant experience, can lead to potentially lethal consequences. Examples of inappropriate remediation efforts that have initiated glacial floods and resulted in the loss of life have been reported from the Peruvian Andes. There is concern that the ongoing work in the Lunana area, Bhutan, could cause catastrophic flooding on a scale not seen in historical times in the Himalayas.

The scale of the problem presented by glacial lakes in Central Asia has not been defined. Glacial hazards, however, can be predicted and successfully managed. Proven techniques are available that allow successful assessment and remediation of potentially dangerous lakes. Compared to the potential losses resulting from glacial flooding, the cost to undertake an assessment for a given area is almost negligible. Also required is the political will to implement policies that tackle the problem at a national and strategic level. Given the finance and the political will, there is no reason why anyone should lose their lives in Central Asia from glacier-related hazards.

Acknowledgements

The authors are very grateful to His Majesty's Government of Nepal (HMG/N) and the Royal Bhutanese Government for providing the opportunity to work on these problems in Nepal and Bhutan, respectively. Thanks are due to the Emergency Aid Department (now the Conflict and Humanitarian Affairs Department) of the Department for International Development, London, for funding three field visits to the Rolwaling, and generally for supporting this ongoing work. The current remediation project at Tsho Rolpa, Nepal, is funded by the Netherlands Development Agency. The work in Bhutan was undertaken in association with Norconsult International A.S./NORPLAN. The authors are also grateful to HMG/N for permission to reproduce the aerial photograph used in Fig. 13, and to Dr Anna Vickery, RGSL, for preparation of the figures.

References

Bhargava, O.N., 1995. Geology, environmental hazards and remedial measures of the Lunana area, Gasa Dzongkhag: report of 1995 Indo-Bhutan Expedition. Geological Survey of India Report.

Björnsson, H., 1974. Explanation of jökulhlaups from Grímsvötn, Vatnajökull Iceland, Jökull 24, 1–26.

Björnsson, H., 1976. Marginal and supraglacial lakes in Iceland. Jökull 26, 40–51.

Björnsson, H., 1992. Jökulhlaups in Iceland: prediction, characteristics and simulation. Annals of Glaciology 16, 96–106.

Chhetri, M.P., 1999. Disaster management in Nepal: Problems and solutions. In: Ingleton, J. (Ed.), Natural Disaster Management. U.N. Secretariat for the IDNDR, Tudor Rose Holdings Ltd, Leicester, pp. 223–224.

Clague, J.J., Evans, S.G., 1994. Formation and failure of natural dams in the Canadian Cordillera. Geological Survey of Canada, Bulletin 464.

Clarke, G.K.C., 1982. Glacier outburst flood from 'Hazard lake', Yukon Territory, and the problems of flood magnitude prediction. Journal of Glaciology 28, 3–21.

Clayton, L., 1964. Karst topography on stagnant glaciers. Journal of Glaciology 5 (37), 107–112.

Costa, J.E., 1988. Floods from dam failures. In: Baker, V.R., Kochel, R.C., Patton, P.C. (Eds.), Flood Geomorphology. Wiley, Chichester, pp. 439–463.

Costa, J.E., Schuster, R.L., 1988. The formation and failure of natural dams. Geological Society of America Bulletin 100, 1054–1068.

Coxon, P., Owen, L.A., Mitchell, W.A., 1996. A Late Quaternary catastrophic flood in the Lahul Himalayas. Journal of Quaternary Science 11 (6), 495–510.

Ding, Y., Liu, J., 1992. Glacial lake outburst flood disasters in China. Annals of Glaciology 16, 180–184.

Fushimi, H., Ohata, T., 1980. Fluctuations of glaciers from 1970 to 1978 in the Khumbu Himal, East Nepal. Seppyo 41, 71–81.

Haeberli, W., 1983. Frequency and characteristics of glacier floods in the Swiss Alps. Annals of Glaciology 4, 85–90.

Hambrey, M.J., 1977. Supraglacial drainage and its relationship to structure, with particular reference to Charles Rabots Bre, Okstindan, Norway. Norsk Geografisk Tidsskrift 31, 69–77.

Hanisch, J., Delisle, G., Pokhrel, A.P., Dixit, A.M., Reynolds, J.M., Grabs, W.E., 1998. The Thulagi glacier lake, Manaslu Himal, Nepal — Hazard assessment of a potential outburst. Proceedings Eighth International Congress, International Association for Engineering Geology and the Environment, 21–25 September, Vancouver, Canada, pp. 2209–2215.

Hanisch, J., Pokhrel, A.P., Dixit, A.M., Grabs, W.E., Reynolds, J.M., 1999. GLOF mitigation strategies — lessons learnt from studying the Thulagi glacier lake. Nepal [abstract]. Journal of Nepal Geological Society 20, 163.

Healy, T.R., 1975. Thermokarst — a mechanism of de-icing ice-cored moraines. Boreas 4, 19–23.

Hewitt, K., 1982. Natural dams and outburst floods of the Karakoram Himalaya. In: Glen, J.W. (Ed.) Hydrological Aspects of Alpine and High Mountain Areas. International Association of Hydrological Scientists, Publication 138. IAHS, Washington, pp. 259–269.

Hewitt, K., 1988. Catastrophic landslide deposits in the Karakoram Himalaya. Science 242, 64–67.

Hewitt, K., 1998. Glaciers receive a surge of attention in the Karakoram Himalaya. Eos, Transations, American Geophysical Union 79 (8), 104–105.

Higuchi, K., Fushimi, H., Ohata, T., Takenaka, S., Iwata, S., Yokoyama, K., Higuchi, H., Nagoshi, A., Iozawa, T., 1980. Glacier inventory in the Dudh Kosi region, east Nepal. World Glacier Inventory, Proceedings of Riederalp Workshop September 1978. IAHS-AISH Publication No. 126, pp. 95–103.

Ives, J.D., 1986. Glacial lake outburst floods and risk engineering in the Himalaya. ICIMOD Occasional Paper 5, 42 pp.

Keylock, C.J., McClung, D.M., Magnússon, M.M., 1999. Avalanche risk mapping by simulation. Journal of Glaciology 45 (150), 303–314.

Kirkbride, M.P., Warren, C.R., 1997. Calving processes at a grounded ice cliff. Annals of Glaciology 24, 116–121.

Leber, D., Häusler, H., Morawetz, R., Schreilechner, M., Wangda, D., 1999. GLOF risk assessment in the Northwestern Bhutanese Himalayas based on remote sensing sustained geo-hazard mapping and engineering geophysical methods [abstract]. Journal of Nepal Geological Society 20, 141.

Lliboutry, L., Morales, B., Pautre, A., Schneider, B., 1977. Glaciological problems set by the control of dangerous lakes in Cordillera Blanca, Peru. I: Historical failure of morainic dams, their causes and prevention. Journal of Glaciology 18 (79), 239–254.

Liu, C., Sharma, C.K. (Eds.), 1988. Report on the first expedition to glaciers and glacier lakes in the Pumqu (Arun) and Poiqu (Bhote-Sun-Kosi) River basins, Xizang (Tibet), China: Sino-Nepalese investigation of glacier lake outburst floods in the Himalaya. Science Press, Beijing, China, 192 pp. plus maps.

Liu, J., 1992. Jökulhlaups in the Kunmalike River, southern Tien Shan mountains. China. Annals of Glaciology 16, 85–88.

MacDonald, K.I., 1989. Impacts of glacier-related landslides on the settlement at Hopar, Karakoram Himalaya. Annals of Glaciology 13, 185–188.

Mayewski, P.A., Jeschke, P.A., 1979. Himalayan and trans-Himalayan glacier fluctuations since AD 1812. Arctic and Alpine Research 11 (3), 267–287.

Mayo, L.R., 1989. Advance of Hubbard Glacier and 1986 outburst of Russell Fiord. Alaska, U.S.A. Annals of Glaciology 13, 189–194.

Mool, P.K., 1995. Glacier lake outburst floods in Nepal. Journal of Nepal Geological Society 11, 273–280.

Nye, J.F., 1976. Water flow in glaciers: jökulhlaups, tunnels and veins. Journal of Glaciology 17 (76), 181–207.

Owen, L.A., 1995. Shaping the Himalayas. Geographical Magazine 12 (2), 23–25.

Pant, S.R., Reynolds, J.M., 1999. Subsurface electrical imaging techniques for the investigation of Thulagi Glacier Lake dam [abstract]. Journal of Nepal Geological Society 20, 80.

Pearce, F., 1999. Hell and high water. New Scientist 19 June 1999, 4.

Perla, R.I., 1980. Avalanche release, motion and impact. In: Colbeck, S.C. (Ed.), Dynamics of Snow and Ice Masses. Academic Press, New York, pp. 397–462.

Rana, B., Reynolds, J.M., Shrestha, A.B., Aryal, R., Pokhrel, A.P., Budathoki, K.P., 1999. Tsho Rolpa, Rolwaling Himal, Nepal: a case history of ongoing glacial hazard assessment and remediation [abstract]. Journal of Nepal Geological Society 20, 242.

Reynolds Geo-Sciences Ltd., 1999. Structural glaciological analysis of Trakarding Glacier, Rolwaling Himal, Nepal. Reynolds Geo-Sciences Ltd Report No. J9857.049, Mold, UK, April 1999.

Reynolds, J.M., 1981. Lakes on George VI Ice Shelf, Antarctica. Polar Record 20 (128), 425–432.

Reynolds, J.M., 1992. The identification and mitigation of glacier-related hazards: examples from the Cordillera Blanca, Peru. In: McCall, G.J.H., Laming, D.J.C., Scott, S.C. (Eds.), Geohazards. Chapman & Hall, London, pp. 143–157.

Reynolds, J.M., 1998. High-altitude glacial lake hazard assessment and mitigation: a Himalayan perspective. In: Maund, J.G., Eddleston, M. (Eds.), Geohazards in Engineering Geology. Geological Society, London, Engineering Geology Special Publications, 15, pp. 25–34.

Reynolds, J.M., 1999a. Photographic feature: glacial hazard assessment at Tsho Rolpa, Rolwaling. Central Nepal. Quarterly Journal of Engineering Geology 32 (3), 209–214.

Reynolds, J.M., 1999b. Glacial hazards in the Himalayas: an overview [abstract]. Journal of Nepal Geological Society 20, 255.

Reynolds, J.M., Richardson, S.D., 1999. Glacial hazards. In: Ingleton, J. (Ed.), Natural Disaster Management. U.N. Secretariat for the IDNDR, Tudor Rose Holdings Ltd, Leicester, pp. 64–65.

Reynolds, J.M., Dolecki, A., Portocarrero, C., 1998. Construction of a drainage tunnel as part of glacial lake hazard mitigation at Hualcán, Cordillera Blanca, Peru. In: Maund, J.G., Eddleston, M. (Eds.), Geohazards in Engineering Geology. Geological Society, London, Engineering Geology Special Publications, 15, pp. 41–48.

Röthlisberger, H., 1977. Ice avalanches. Journal of Glaciology 19 (81), 669–671.

Schweizer, J., Föhn, P.M.B., 1996. Avalanche forecasting — an expert system approach. Journal of Glaciology 42 (141), 318–332.

Sharma, A.R., Ghosh, D.K., Norbu, P., 1987. Report on Lunana Lake Expedition — 1986. Geological Survey of India Report.

Sharp, M., 1988. Surging glaciers: behaviour and mechanisms. Progress in Physical Geography 12, 349–370.

Shiraiwa, T., Yamada, T., 1991. Glacier inventory of the Langtang Valley, Nepal Himalayas. Low Temperature Science, Ser. A, 50, Data Report, pp. 47–72.

Tashi, T., 1994. Preliminary report on the investigation of glacial lakes at Pho Chhu source and the assessment of flood affected areas in Lunana. Royal Bhutanese Government Report.

Thorarinsson, S., 1939. The ice-dammed lakes of Iceland, with particular reference to their values as indicators of glacier oscillations. Geografiska Annaler 21, 216–242.

Vuichard, D., Zimmermann, M., 1986. The Langmoche flash-flood, Khumbu Himal, Nepal. Mountain Research and Development 6 (1), 90–93.

Vuichard, D., Zimmermann, M., 1987. The 1985 catastrophic drainage of a moraine-dammed lake, Khumbu Himal, Nepal: cause and consequences. Mountain Research and Development 7 (2), 91–110.

Walder, J.S., Costa, J.E., 1996. Outburst floods from glacier-dammed lakes: the effect of mode of lake drainage on flood magnitude. Earth Surface Processes and Landforms 21, 701–723.

Walder, J.S., Driedger, C.L., 1995. Frequent outburst floods from South Tahoma Glacier, Mount Rainier, U.S.A.: relation to debris flows, meteorological origin and implications for subglacial hydrology. Journal of Glaciology 41 (137), 1–10.

Warburton, J., Fenn, C.R., 1994. Unusual flood events from an Alpine glacier: observations and deductions on generating mechanisms. Journal of Glaciology 40 (134), 176–186.

Warren, C.R., Greene, D.R., Glasser, N.F., 1995. Glacier Upsala, Patagonia: rapid calving retreat in fresh water. Annals of Glaciology 21, 311–316.

Watanabe, T., Kameyama, S., Sato, T., 1995. Imja Glacier dead-ice melt rates and changes in a supra-glacial lake, 1989–1994, Khumbu Himal, Nepal: Danger of lake drainage. Mountain Research and Development 15 (4), 293–300.

Yamada, T., 1993. Glacier lakes and their outburst floods in the Nepal Himalaya. Water and Energy Commission Secretariat, Kathmandu, Nepal, 37 pp.

Yamada, T., 1998. Glacier lake and its outburst flood in the Nepal Himalaya. Monograph No. 1, Data Centre for Glacier Research, Japanese Society of Snow and Ice, Japan, pp. 96.

Yamada, T., Shiraiwa, T., Iida, H., Kadota, T., Watanabe, T., Rana, B., Ageta, Y., Fushimi, H., 1992. Fluctuations of the glaciers from the 1970s to 1989 in the Khumbu, Shorong and Langtang regions. Nepal Himalayas. Bulletin of Glacier Research 10, 11–19.

Zhang, W., 1992. Identification of glaciers with surge characteristics on the Tibetan Plateau. Annals of Glaciology 16, 168–172.

Zhang, X., 1992. Investigation of glacier bursts of the Yarkant River in Xinjiang. China. Annals of Glaciology 16, 135–139.