1 Introduction

The Hindu Kush-Himalayan (HKH) region embraces the greatest agglomeration of high mountains and plateaus in the world. It consists of many distinct, but inter-connected, mountain ranges and plateaus, extending for more than 3,500 km from the Hindu Kush of Afghanistan and Pakistan in the northwest, to the Hengduan Mountains in southwest China in the east. Backed by the immense Tibetan Plateau and multiple mountain ranges from the High Pamir to the Tien Shan, Kun Lun Shan, and Qilian Shan, this 'roof-of-the-world' land mass is one of the major components affecting world climate circulation. It also contains the world's highest mountains, including many in excess of 8,000 metres, together with the world's greatest areal extent and volume of permanent ice and permafrost outside the polar regions. Without doubt, it is central for any understanding of the effects of the current climate warming. One special element of the process of climate warming is its impact on the glaciers, and especially on the development of potentially dangerous glacial lakes within the Hindu Kush-Himalayan region. This is the central point of the present report.

A cautionary note must be added, however, to qualify the use of the phrase 'potentially dangerous glacial lakes'. The word 'potential' or 'potentially', as used in the scientific/scholarly literature will often differ in meaning from its use in popular writing, and especially in the news media. Current understanding of the highly complex process of glacier thinning and retreat and, in certain instances, of the formation of meltwater lakes as part of this process, is still rudimentary. Thus, precise determination of the degree of risk is not possible. Nevertheless, because it is well established that glacial lakes have discharged precipitously in the recent past (last 50 years) and caused loss of life and damage to infrastructure farther downstream, it must be assumed that other lakes in apparently similar situations may do so at some time in the future. Such risks must be analysed. Any responsible assessment, however, should never include an attempt to provide a precise date nor any determination of actual magnitude. The approach should be to propose the possibility of such an event and to outline steps to be taken to avert, or at least minimise, human losses if such were to occur. Such lakes can also be described as 'critical', in other words they appear to have some potential for catastrophic breaching that should be investigated, but the likely risk may be low, medium, or high.

The Hindu Kush-Himalayan land mass has much more than regional high mountain significance. Its interaction with the Indian monsoon system, together with seasonal melt of snow and glacier ice, affects the supply of vital water to many of the world's greatest rivers. The lower reaches of these river basins, beyond the mountains, provide essential nourishment for almost a third of humanity.

The International Centre for Integrated Mountain Development (ICIMOD) was established in 1982 as a regional knowledge development and learning centre serving the eight member countries of the Hindu Kush-Himalayas – Afghanistan, Bangladesh, Bhutan, China, India, Myanmar, Nepal, and Pakistan – and based in Kathmandu, Nepal. Globalisation and climate change have an increasing influence on the stability of fragile mountain ecosystems and the livelihoods of mountain people. ICIMOD aims to assist mountain people to understand these changes, adapt to them, and make the most of new opportunities, while addressing upstream-downstream issues. The centre supports transboundary programmes through collaboration with partner institutions, facilitates the exchange of experiences and serves as a regional knowledge hub. It also strengthens networking among regional and global centres of excellence. Overall, the work aims to develop an economically and environmentally sound mountain ecosystem, to improve the living standards of mountain populations and to sustain vital ecosystem services for the millions of people living downstream – now, and for the future.

Glaciers in many parts of the HKH region are currently thinning and retreating, presumably as a result of the current climate warming. Glacial lakes often form between the frontal moraine and the retreating glacier or on the surface of the lower section of the glacier. These kinds of lakes are held back (dammed) by more or less unstable moraine complexes, and have a potential to breach their moraine dams. This phenomenon, in the Himalayas and elsewhere, has become known as a glacial lake outburst flood (or GLOF) and has the potential for generating extensive destruction in the valley downstream. The impact of such an outburst depends on the physical character of the dam, the lake size and depth and the rapidity of its drainage, and the nearby surroundings. Glacial hazards, such as ice avalanches, GLOFs, and debris flows, have caused severe damage in populated mountain regions in the HKH (and in many mountain areas throughout the world), and there is a concern that their frequency could increase as a result of accelerated glacial thinning and retreat. In certain circumstances, a GLOF can instantaneously release a huge amount of water and debris. This most likely would cause extensive effects on the downstream areas posing a threat to human lives and infrastructure. Thus, GLOF risk assessment has become an issue of considerable significance that must be dealt with.

Glacial lake outburst flood events

Glacial lake outburst floods have long been known to occur in different parts of the world. In 1941, an outburst flood destroyed the city of Huaraz in Peru killing 4,500 people (Lliboutry et al. 1977). Outbursts from a glacier-dammed lake in the Swiss Alps in 1968 and 1970 triggered debris flows and caused heavy damage in the village of Saas Balen. The 1968 event eroded about 400,000 cubic metres of debris (Horstman 2004).

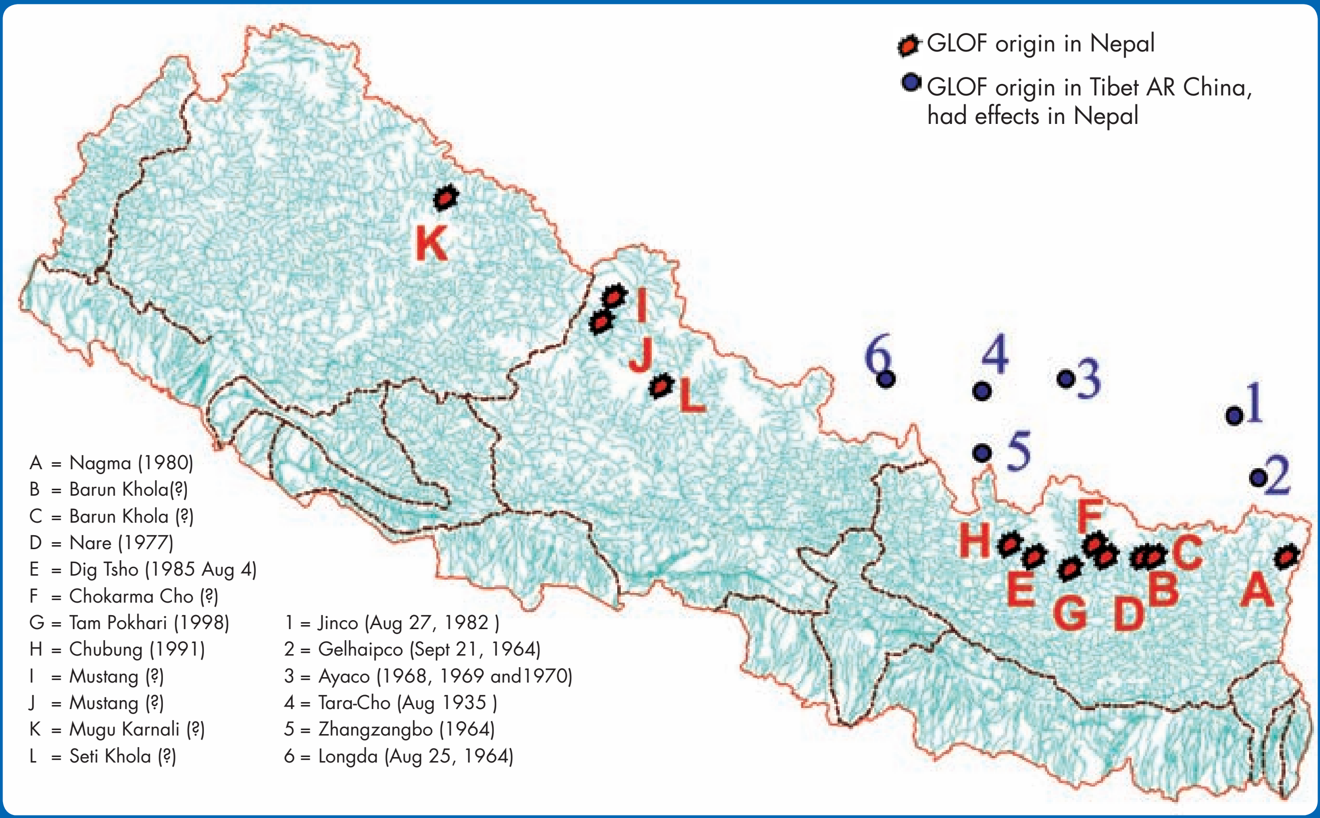
Although, glacial lake outburst floods have occurred in various parts of the Hindu Kush-Himalayan region in the past, known both from the living memories of local people and from incidentally documented evidence; precise location, frequency, and actual scale of their effects are not adequately known or documented. Scientific investigation has revealed, for example, that a glacial lake outburst flood occurred along the Seti Khola about 450 years ago. It produced a debris deposit up to 50 metres deep that mantled an extensive area of the Pokhara valley in western Nepal. The specific event appears to have been the catastrophic outbreak of a lake behind Machhapuchare mountain, probably triggered by seismic activity (Carson 1985). This appears as a singular historic event. Nevertheless, closer to the present, it appears that glacial lake outbursts have occurred more frequently, especially during the last half century, and the reporting record has greatly improved.

There are indications that earlier recordings of flash floods in the Ladakh Range in Jammu and Kashmir were actually glacial lake outbursts far upstream (Gergan et al. 2009). Such catastrophic events that propagate for considerable distances downstream from their point of origin are also liable to cross international frontiers. This characteristic renders them of exceptional concern because of the obvious political implications of assessing responsibility (if any) for loss of life and property damage. There are well-documented examples whereby lake outbursts have occurred in Tibet AR (China) and have crossed the international borders into Nepal and Bhutan (Figure 1 and Table 1). Table 1 shows the recorded history of glacial lake outburst events which have occurred in Bhutan, the Pumqu (Arun) and Poiqu (Bhote-Sunkoshi) basins in Xizang (TAR China), and Nepal (Mool 1995; Mool et al. 2001a and 2001b; Yamada 1998a; Bajracharya et al. 2008).

Despite the scale of the risk, it is possible to assess and mitigate the hazards successfully. Hazard assessment using satellite images has been applied to remote areas of Nepal and Bhutan and remediation techniques have been attempted in both countries. The purpose of the current assignment is to assess ongoing work by various agencies utilising remote sensing for monitoring the GLOF risk. The specific objective is to promote understanding of this ongoing utilisation, to identify gaps, and to provide recommendations for the future.

Damage caused by the outbreak of glacial lakes in the HKH region is by no means the only threat from what can be generalised as 'flash floods'. Such phenomena are also caused by the temporary damming of river courses by avalanches, landslides, rock falls, and similar events that restrict the normal flow of a river, and by torrential monsoon downpours. The understanding arising from the study of GLOFs and their causes will have some relevance to the broader category of the rapid discharge of waters.

Figure 1: **Recorded glacial lake outburst events in the central Himalayan region that have affected Nepal and TAR/China**



Source: Mool et al. (2001a)

Table 1: **List of known GLOF events that have occurred in Nepal, TAR/China, and Bhutan**
(after Mool et al. 1995, 2001a, 2001b; Yamada 1998a; and Bajracharya et al. 2008)

	Date	River Basin	Lake	Source	Cause of GLOF	Losses	Latitude	Longitude
Bhutan								
1	1957	Pho Chu	Tarina Tso	Bhutan	Not known		28° 06′ 06″	89° 54′ 11″
2	1960	Pho Chu	Unnamed	Bhutan	Not known		eastern Lunana	
3	1960?	Chamkhar Chu	Bachamancha Tso	Bhutan	Not known		28° 01′ 55″	90° 40′ 41″
4	7 Oct 94	Pho Chu	Luggye Tso	Bhutan	Moraine collapse		28° 05′ 00″	90° 18′ 28″
China (TAR)								
5	10 Jun 40	Kangboqu-Ahmchu	Qubixiama-Cho	TAR, China (North of Sikkim)	Ice avalanche			
6	16 Jul 54	Nyangqu	Sangwang-Cho	TAR, China (North of Bhutan)	Glacier advance			
7	26 Sep 64	Tangbulang (Nyang)	Damenhai-Cho	TAR, China	Ice avalanche			
8	23 Jul 72	Xibaxiaqu	Poge-Cho	TAR, China	Ice avalanche			
9	24 Jun 81	Yarlung Zangbo	Zari-Cho	TAR, China	Ice avalanche			
10	14 Jul 88	Palong Zangbo	Mitui-Cho	TAR, China	Ice avalanche			

Table 1: Cont....

	Date	River Basin	Lake	Source	Cause of GLOF	Losses	Latitude	Longitude
China (TAR), also affecting Nepal downstream								
11	Aug 35	Sunkoshi	Tara-Cho	TAR, China	Piping	66,700 m^2 of wheat field, livestock, others	28° 17′ 00″	86° 08′ 00″
12	21 Sep 64	Arun	Gelhaipco	TAR, China	Glacier surge	Highway and 12 trucks	27° 58′ 00″	87° 49′ 00″
13	1964	Sunkoshi	Zhangzangbo	TAR, China	Piping	No remarkable damage	28° 04′ 01″	86° 03′ 45″
14	25 Aug 64	Trisuli	Longda	TAR, China	Not known	Not known	28° 37′ 01″	85° 20′ 58″
15	1968	Arun	Ayaco	TAR, China	Not known	Road, bridges, others	28° 21′ 00″	86° 29′ 00″
16	1969	Arun	Ayaco	TAR, China	Not known	Not known	28° 21′ 00″	86° 29′ 00″
17	1970	Arun	Ayaco	TAR, China	Not known	Not known	28° 21′ 00″	86° 29′ 00″
18	11 Jul 81	Sunkoshi	Zhangzangbo	TAR, China	Glacier surge	Hydropower station	28° 04′ 01″	86° 03′ 45″
19	27 Aug 82	Arun	Jinco	TAR, China	Glacier surge	Livestock, farmland	28° 00′ 35″	87° 09′ 39″
20	6 Jun 95	Trisuli	Zanaco	TAR, China	Not known		28° 39′ 44″	85° 22′ 19″
Nepal								
21	450 years ago	Seti Khola	Machhapuchhare	Nepal	Moraine collapse	Pokhara valley covered by 50-60m debris	28° 31′ 13″	83° 59′ 30″
22	3 Sep 77	Dudh Koshi	Nare	Nepal	Moraine collapse	Mini hydropower plant	27° 49′ 47″	86° 50′ 12″
23	23 Jun 80	Tamor	Nagma Pokhari	Nepal	Moraine collapse	Villages destroyed 71 km from source	27° 51′ 57″	87° 51′ 46″
24	4 Aug 85	Dudh Koshi	Dig Tsho	Nepal	Ice avalanche	Hydropower station, 14 bridges, and others	27° 02′ 36″	86° 35′ 02″
25	12 Jul 91	Tamakoshi	Chubung	Nepal	Moraine collapse	Houses, farmland and so on	27° 52′ 37″	86° 27′ 38″
26	3 Sep 98	Dudh Koshi	Tam Pokhari	Nepal	Ice avalanche	Human lives and more than NRs 156 million	27° 44′ 20″	86° 50′ 45″
27	Unknown	Arun	Barun Khola	Nepal	Moraine collapse	Details not known	27° 50′ 33″	87° 05′ 01″
28	Unknown	Arun	Barun Khola	Nepal	Moraine collapse	Details not known	27° 49′ 46″	87° 05′ 42″
29	Unknown	Dudh Koshi	Chokarma Cho	Nepal	Moraine collapse	Details not known	27° 54′ 21″	86° 54′ 48″
30	Unknown	Kali Gandaki	Unnamed (Mustang)	Nepal	Moraine collapse	Details not known	29° 13′ 14″	83° 42′ 09″
31	Unknown	Kali Gandaki	Unnamed (Mustang)	Nepal	Moraine collapse	Details not known	29° 07′ 03″	83° 44′ 19″
32	Unknown	Mugu Karnali	Unnamed (Mugu Karnali)	Nepal	Moraine collapse	Details not known	29° 39′ 00″	82° 48′ 00″
33	15 Aug 03	Madi River	Kabache Lake	Nepal	Moraine collapse	Details not known		
34	8 Aug 04	Madi River	Kabache Lake	Nepal	Moraine collapse	Details not known		