ICIMOD

Formation of Glacial Lakes in the Hindu Kush-Himalayas and GLOF Risk Assessment

ISDR International Strategy for Disaster Reduction

GFDRR Global Facility for Disaster Reduction and Recovery

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FOR MOUNTAINS AND PEOPLE

Formation of Glacial Lakes in the Hindu Kush-Himalayas and GLOF Risk Assessment

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Foreword

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Glaciers are believed to have persisted in the Hindu Kush-Himalayas since the last Ice Age (which ended about 10,000 years ago). At present, world glacial ice cover is most widely distributed in Antarctica and Greenland. Nevertheless, the Hindu Kush-Himalayan region is one of the most heavily glacierized areas in the world outside the polar regions. Glacier ice covers approximately 33,000 square kilometres in the Himalayan range alone. Thus, explorers, mountaineers, scientists, researchers, developers, and planners, have been attracted to the area for the last 200 years. The extensive permanent ice and snow cover forms the headwater supply of some of the world's largest rivers. This in turn is vital for the provision of life-supporting water and hydroelectricity for almost one-third of the world's population, living in the lower river basins beyond the mountains. However, the combination of extremely high mountains, high seismic activity, and steep slopes is also responsible for a wide range of natural hazards, including landslides, flash floods, avalanches, and glacial lake outburst floods.

It has been widely recognised that global climate change is causing the shrinkage or retreat of glaciers throughout the world. The Hindu Kush-Himalayan region is no exception. This has resulted in the formation of a large number of glacial lakes, many of which can become unstable as their volume increases or they are subjected to surge waves as a result of ice and rock avalanches striking their surface that cause them to overtop their end moraine dams. A number of glacial lake outburst floods (GLOFs) have occurred in the Hindu Kush-Himalayas in recent years, some of which have caused considerable damage across international borders. Lives have been lost, livelihoods destroyed, and extensive damage to infrastructure has occurred.

Monitoring ice and water resources, promoting community resilience and preparedness for disaster risk reduction, and ensuring the sharing of upstream-downstream benefits are priority areas in ICIMOD's programme. As glaciers and glacial lakes are related both to water resources and to water-related natural hazards, they need to be mapped and monitored.

While glaciological research has been carried out in the Hindu Kush-Himalayan region by many institutions and individuals (principally academic) over more than a century, the research has been intermittent with no systematic or coordinated long-term basis. Given the vast area involved and problems of accessibility and high altitude, and despite many invaluable results, the entire region remains little known compared to such areas as the European Alps, Scandinavia, and western North America. ICIMOD is attempting to bridge the knowledge gap by undertaking a systematic inventory of glaciers and glacial lakes, and identifying those lakes that could represent a threat. This large programme, heavily dependent on remote sensing, has been developed in collaboration with ICIMOD's country partners. More than 8,000 glacial lakes have been identified. While the great majority of these are very small and have formed in remote areas, up to 200 may be potentially dangerous.

The potential for serious losses due to GLOFs is likely to increase as climate warming progresses through the 21st century; new lakes are forming and existing ones are enlarging. Hence, a standardised glacial lake inventory is being prepared for the entire Hindu Kush-Himalayan region and will be used as a basis for GLOF risk assessment, supported by the Swedish International Development Cooperation Agency, the Norwegian Ministry of Foreign Affairs, and the World Bank.

We hope that the present report, which provides a detailed background to the present situation, will help fulfil the requirement for regional knowledge about glacial lakes and GLOF risk. In this way, planners and policy makers, as well as development scientists, will have a tool to facilitate regional collaboration aimed at reducing the glacial lake hazard.

On behalf of ICIMOD, I would like to thank the Swedish International Development Cooperation Agency, the Norwegian Ministry of Foreign Affairs, and the World Bank for their support. The assistance in preparation of this report provided by the United Nations International Strategy for Disaster Reduction (UNISDR) and the Global Facility for Disaster Reduction and Recovery (GFDRR)/World Bank is gratefully acknowledged.

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Foreword

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Himalaya is a Sanskrit word that translates as 'abode of snow'. Today, this glacial abode, forming the largest body of ice outside the polar latitudes, is shrinking. Though the rate of melting and retreat varies, and glacier advance is occurring in some areas, the overall negative trend is evident. The wider Himalayan system extends across eight countries: Afghanistan, Bangladesh, Bhutan, China, India, Myanmar, Nepal, and Pakistan and supports ten river systems – the Amu Darya, the Brahmaputra, the Ganges, the Indus, the Irrawaddy, the Mekong, the Salween, the Tarim, the Yangtze, and the Yellow. These river systems provide water and sustain food supplies for over 1.3 billion people.

Accelerated glacial melt increases the risk of avalanches and floods, and causes lakes formed from melting glaciers to expand. Many Himalayan basins report fast growing lakes greatly increasing the threat of glacial lake outburst floods (GLOFs). Glacial lakes bursting their banks can have catastrophic consequences for people, agriculture and hydropower infrastructure downstream.

It is estimated that there are over 8,000 glacial lakes in the Hindu Kush-Himalayan region with more than 200 of them identified as potentially dangerous. A GLOF event of 1985 originating from Dig Tsho, a glacial lake in the Khumbu Himal, Nepal, destroyed the nearly completed Namche Small Hydel Project and caused extensive damage downstream. GLOFs have caused damage across national borders; outbursts originating in China have impacted areas in Nepal, India, and Bhutan.

Glacial lakes pose a threat to their downstream communities, but they are also a potential source of water storage for sustaining agriculture and forest-based livelihoods. The challenge is to minimise the risk of outburst and to reduce the vulnerability of nearby communities while securing the potential benefits of the lakes. Scientific information about existing glacial lakes, enhanced by monitoring and early warning systems, and mitigation measures to reduce the impact of glacial melting is essential.

The South Asia programme of the Global Facility for Disaster Reduction and Recovery (GFDRR) in partnership with the United Nations International Strategy for Disaster Reduction (UNISDR) has given high priority to the sub regional issues of GLOFs. This technical assessment study of GLOF risks in the Hindu Kush-Himalayan region, by the International Centre for Integrated Mountain Development (ICIMOD), pays special attention to the impact of GLOFs and their transboundary nature. It aims to encourage inter-country dialogue, to develop appropriate policies, and to generate the required investments.

We hope that this will be a step towards achieving greater regional cooperation and consensus for effective GLOF risk reduction and mitigation in the South Asia region.

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Executive Summary

This report contains an assessment of the threat facing the Hindu Kush-Himalayan region from the recent (post-1950s) and rapid formation of meltwater lakes on the surface or at the end of a large number of the region's glaciers. There is no doubt that the driving force is the current climate warming. Individual case studies of the catastrophic outburst (glacial lake outburst floods or GLOFs) from such glacial lakes are introduced. The potential for acceleration of extensive downstream damage and loss of life is high. Equally, there have been many occasions in the news media, and even in the scientific literature, where the threat has been exaggerated to the point of becoming melodrama. An attempt is made here to modify this potentially damaging misrepresentation.

Early responses up to the present are described together with the methods employed, including remote sensing and geophysical field investigations. A list is provided of the several institutions with responsibility for assessing the GLOF problem within their own prescribed sections of the region. Already, several bilateral and trilateral associations have evolved, with ICIMOD playing the role of facilitator.

The critical importance of continued and extended application of a wide variety of remote sensing techniques is underlined. However, it is also stressed that once a realistic ranking of the glacial lakes in order of their perceived degree of danger is firmly in place, detailed glaciological and geophysical field investigation will be required. Remote sensing application is the primary tool to achieve this in view of the serious challenges posed by high altitude, vast areal extent, and difficult accessibility. Enough is known already, such that action does not need to await lengthy scientific investigation. Nevertheless, it is emphasised that precise identification of the timing and magnitude of potential outbreak of glacial lakes cannot be achieved with the present state of knowledge. Consequently, the report aims to present a preliminary assessment as a basis for future action.

As understanding of the hazard advances, effective warnings should reach every person at risk in a timely manner. Likewise, mitigation measures applied to reduce the loss of life and property from the GLOF risk should be such that they should not create or increase the risk during and after the time that the proposed mitigation measures are being put in place. The early warning systems that have been installed in Nepal and Bhutan are described and warning systems employed in other countries are also mentioned. Similarly, examples of mitigation measures taken in Nepal and Bhutan are discussed.

Regional collaboration among or between the governments in the event of transboundary disasters such as GLOF risk assessment and mitigation, as well as sharing of data and information for GLOF risk management, is essential. Also, there is a need to accelerate inter-governmental collaborative research on glacial hazards and GLOF risk management. The importance of national policy development in GLOF risk management is also emphasised. Regional centres of excellence such as ICIMOD can play a critical role in bringing knowledge to guide policy making on GLOF risk reduction. A regional convention involving relevant government authorities and expert groups is proposed to develop the next steps in GLOF risk management.

Contents

Dig Tsho glacial lake, Nepal, in April 2009 (after August 1985 GLOF)

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).

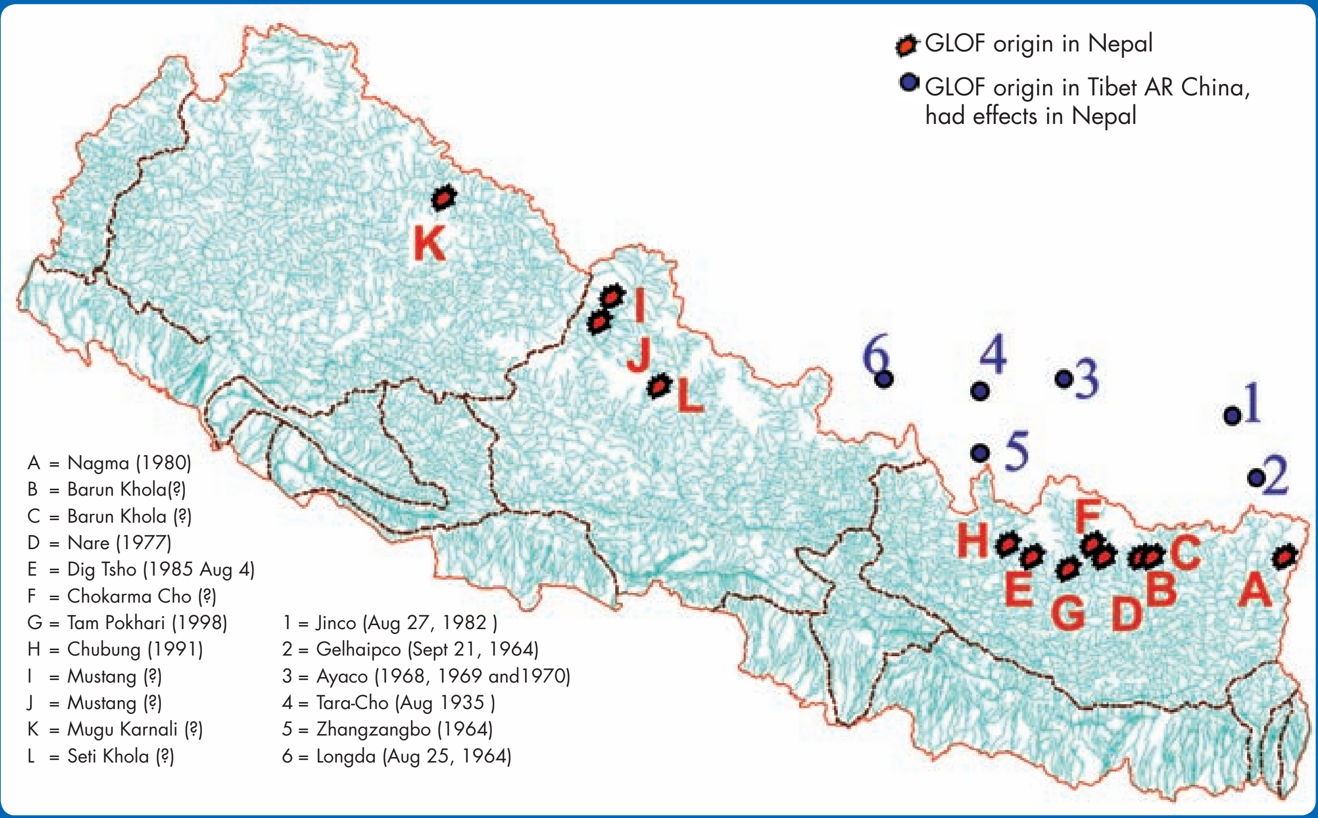
Although, glacial lake outburst floods have occurred in various parts of the Hindu Kush-Himalayan region in the past, known both from the living memories of local people and from incidentally documented evidence; precise location, frequency, and actual scale of their effects are not adequately known 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		

2 Glacial Lakes in the Hindu Kush-Himalayas

Background

On 11 July, 1981, the diversion weir at the Sunkoshi Hydro-electricity Project, Nepal, was struck by a large flood and incurred significant damage. The flood also destroyed two bridges and extensive sections of the Arniko Highway, resulting in some US $3.0 million in damages (Mool et al. 2001). At the time, the actual cause of the flood was not known. On 4 August, 1985, an outburst flood from Dig Tsho (a glacial lake in the Khumbu Himal, Nepal), totally destroyed the nearly completed Namche Small Hydel Project and caused additional extensive damage farther downstream (Ives 1986; Vuichard and Zimmerman 1987). In the same year, Xu (1988) published a paper that identified the cause of the 1981 flood. He demonstrated that it resulted from the outbreak of the Zhangzangbo (Boqu) glacial lake within China (TAR) that crossed the international border into Nepal.

The combined events prompted the Water and Energy Commission Secretariat (WECS) of Nepal to begin an investigation of the potential threat of glacial lake outburst floods (GLOFs). A substantial body of work was accomplished. The ensuing report (WECS 1987) included the first attempt to inventory glacial lakes in Nepal, to discuss the problems of mitigation, and to explore the possibility of establishing early warning systems in susceptible areas. The WECS investigation was sponsored by the Canadian International Development Agency (CIDA) and ICIMOD. WECS, in collaboration with Lanzhou Institute of Glaciology and Geocryology (LIGG) of the Chinese Academy of Sciences, carried out an inventory based on topographic maps of the 1980s, aerial photographs of 1974 and field investigations of selected glacial lakes of the Pumqu (Arun) and Poiqu (Bhote Koshi-Sunkoshi) river basins in TAR, China in 1987 (LIGG/WECS/NEA 1988).

Mapping of glaciers is also needed in conjunction with the study of glacial lakes. In this context, glacier mapping information is available for the Indian Himalaya as well as for other regions. The Glaciology Division of the Geological Survey of India (GSI) took up systematic glaciological studies in 1974 after its establishment, although conventional studies of a number of isolated Himalayan glaciers had been carried out previously. Beginning with a pilot study of the Baspa basin in the Sutlej catchment by Vohra and Agarwal in 1978, in accordance with the UNESCO (United Nations Educational, Scientific and Cultural Organization) (1970) manual for conducting such inventories, a preliminary survey was undertaken and compiled by V.K. Raina, Geological Survey of India. It covered the upper Indus, Chenab, Ravi, Ganga, and Sutlej basins and was followed by a study of the Jhelum basin of Kashmir, part of the Sutlej basin of Himachal Pradesh, the Bhagirathi basin of Garhwal, the Tista basin of Sikkim and part of the Brahmaputra basin of Arunachal Pradesh. These inventories used the Survey of India topographic maps (scales 1:50,000 or 1:250,000 whichever were available), aided by vertical aerial photographs and satellite imagery (Puri et al. 1999).

The Geological Society of India (2008) published the 'Glacier Atlas of India' in order to provide an accurate and up to date metric plan representation of the existing glacier cover for the Indian part of the Himalayas (Raina and Srivastava 2008). Glacier processes and landforms, including glacial lakes, are mentioned in the report, although no systematic mapping of glacial lakes was undertaken.

China also carried out a country-wide glacier inventory between 1979 and 2002. This was made available in the form of 22 separate documents.

ICIMOD has been involved in glacier and glacial lake inventory and the identification of potentially dangerous glacial lakes since 1986 (e.g., Ives 1986). An initial association with WECS was maintained. WECS evaluated the status of the glacial lakes in Nepal and prioritised individual lakes for further assessment. Field examination of Dig Tsho, Imja Tsho, Tsho Rolpa and the Lower Barun glacial lakes was carried out during 1991-1994 (Mool 1995). WECS extended its exploration with financial assistance from the Japanese International Cooperation Agency (JICA) together with expert advice and direct involvement of several Japanese glaciologists (e.g.,Yamada1998a). Hanisch, together with a team of co-workers, introduced experimental electrical resistivity tomography and low frequency ground penetrating radar in an analysis of the sub-surface conditions of end moraines damming the Thulagi glacial lake in the Manaslu Himal, Nepal (Hanisch et al. 1998) which also contributed to the identification of Thulagi glacial lake as potentially dangerous.

The ICIMOD inventory studies

Between 1999 and 2005, ICIMOD in collaboration with partners in different countries, embarked on the preparation of an inventory of glaciers and glacial lakes, and identification of potential sites for glacial lake outburst floods ('potentially dangerous' glacial lakes), in the Hindu Kush-Himalayan region, using desk-based studies and systematic application of remote sensing. The inventory for Nepal and Bhutan was started in 1999 in cooperation with the United Nations Environment Programme/Regional Resources Centre for Asia and the Pacific (UNEP/RRC-AP), and published in 2001(Mool et al. 2001a and Mool et al. 2001b). Inventories for selected basins in China, India, and Pakistan were started in 2002 with the support of Asia-Pacific Network for Global Change Research (APN), the global change SysTem for Analysis, Research, and Training (START), and UNEP/RRC-AP. Figure 2 shows the approximate geographical area covered by the various studies.

The inventories for Bhutan and Nepal were prepared from analyses of published maps, in most cases from between 1950 and the 1970s, and from analyses of more recent remote sensing images for the other countries. Analysis of the development of lakes was based on a comparison of the remote sensing images and the maps. The individual studies are described in more detail in the following together with selected results from other studies. Details are provided in the individual publications of the studies cited in the following paragraphs. Table 2 summarises the main findings of the studies in Bhutan, China (Ganges sub basins), India, Nepal, and Pakistan.

Figure 2: **Location of regional inventories of glaciers and glacial lakes in Bhutan, China, India, Nepal, and Pakistan prepared by ICIMOD together with national partners (1999-2005) (borders indicative)**

Table 2: **Summary of glaciers, glacial lakes, and lakes identified as potentially dangerous in selected parts of Bhutan, China, India, Nepal and Pakistan** (sources given in the text)

River basin	Glaciers			Glacial lakes		
	Number	Area (sq.km)	Ice reserves (cu.km)	Number	Area (sq.km)	Potentially dangerous
Bhutan						
Amo Chu	0	0	0.00	71	1.83	0
Wang Chu	36	49	3.55	221	6.47	0
Puna Tsang Chu	272	503	43.27	980	35.08	13
Manas Chu	310	377	28.77	1383	55.51	11
Nyere Ama Chu	0	0	0.00	9	0.07	0
Northern basins	59	388	51.72	10	7.81	0
Total	**677**	**1317**	**127.31**	**2674**	**106.77**	**24**
China (Ganges sub basins within China)						
Jiazhagangge	96	143	NA	14	0.52	1
Daoliqu	43	60	"	7	0.38	-
Majiacangbu	147	216	"	69	4.73	11
Jilongcangbu	180	419	"	72	3.32	2
Poiqu	127	231	"	91	15.66	9
Pumqu	716	1408	"	383	52.01	38
Rongxer	205	301	"	183	8.40	16
Zangbuqin	64	86	"	5	0.18	-
Total	**1578**	**2864**	**"**	**824**	**85.19**	**77**
India						
Himachal Pradesh						
Beas	358	758	76.40	59	236.20	5
Ravi	198	235	16.88	17	9.16	1
Chenab	681	1705	187.66	33	3.22	5
Satluj	945	1218	94.45	40	136.46	3
Sub-basins	372	245	11.96	7	0.18	2
Total	**2554**	**4161**	**387.35**	**156**	**385.22**	**16**
Uttaranchal (Uttarakhand)						
Yamuna	124	173	17.88	20	0.17	0
Bhagirathi	393	1034	143.41	32	0.44	0
Alaknanda	540	1675	191.36	54	1.37	0
Kali	382	1178	122.78	21	0.51	0
Total	**1439**	**4060**	**475.43**	**127**	**2.49**	**0**
Tista river basin (Total)	**285**	**577.**	**64.78**	**266**	**20.20**	**14**
Nepal						
Koshi River	779	1410	152.06	1062	25.09	16
Gandaki River	1025	2030	191.39	338	12.50	4
Karnali River	1361	1740	127.81	907	37.67	0
Mahakali River	87	143	10.06	16	0.38	0
Total	**3252**	**5324**[a]	**481.32**	**2323**	**75.64**	**20**
Pakistan (Indus river basin)						
Swat	233	224	12.22	255	15.86	2
Chitral	542	1904	258.82	187	9.36	1
Gilgit	585	968	83.34	614	39.17	8
Hunza	1050	4677	808.79	110	3.21	1
Shigar	194	2240	581.27	54	1.09	0
Shyok	372	3548	891.80	66	2.68	6
Indus	1098	688	46.38	574	26.06	15
Shingo	172	37	1.01	238	11.59	5
Astor	588	607	47.93	126	5.52	9
Jhelum	384	148	6.94	196	11.78	5
Total	**5218**	**15041**	**2738.50**	**2420**	**126.32**	**52**
Grand Total	**15,003**	**33,344**	**NA**	**8,790**	**801.83**	**203**

Note: The Thorthormi lake in Bhutan has also been identified as potentially dangerous (Karma et al. 2008)

[a] Total is higher than addition total as a result of rounding.

Criteria for defining 'potentially dangerous' or critical lakes

A step-by-step approach was taken by ICIMOD during the inventory study to identify potentially dangerous lakes, i.e., critical lakes warranting further investigation. The criteria used to identify these lakes are based on field observations, processes and records of past events, geomorphological and geo-technical characteristics of the lake and surroundings, and other physical conditions. Identification was also based on the condition of lakes, dams, associated glaciers, and topographic features around the lakes and glaciers. The major criteria used were as follows (Mool et al. 2001a; Mool et al. 2001b; Mool and Bajracharya 2003; Bhagat et al. 2004; Sah et al. 2005; Roohi et al. 2005; Wu Lizong et al. 2005):

1. Large lake size and rapid growth in area
2. Increase in lake water level
3. Activity of supra-glacial lakes at different times
4. Position of the lakes in relation to moraines and associated glacier
5. Dam condition
6. Glacier condition
7. Physical conditions of surroundings

Dam condition

a) Narrow crest area
b) No drainage outflow or outlet not well defined
c) Steepness of slope of the moraine walls
d) Existence and stability of ice core and/or permafrost within moraine
e) Height of moraine
f) Mass movement, or potential mass movement, on the inner slope and/or outer slope of moraine
g) Breached and closed in the past and the lake refilled with water
h) Seepage through the moraine walls

Glacier condition

a) Condition of associated glacier
b) Hanging glacier in contact with lake
c) Large glacier area
d) Rapid glacier retreat
e) Debris cover on the lower glacier tongue
f) Gradient of glacier tongue
g) Presence of crevasses and ponds on glacier surface
h) Toppling/collapsing of ice from the glacier front
i) Ice blocks draining to lake

Physical conditions of surroundings

a) Potential rockfall/slide (mass movement) sites around the lake
b) Large snow avalanche sites immediately above the lake
c) Neo-tectonic and earthquake activities around or near the lake
d) Climatic conditions, especially large inter-annual variations
e) Very recent moraines of tributary glaciers that were previously part of a former glacier complex, and with multiple lakes that have developed due to glacier retreat (e.g. Lunana area in Pho Chu basin in Bhutan)
f) Sudden advance of a glacier towards a lower tributary or main glacier which has a well-developed frontal lake

Spot field checking is necessary for glacial lakes that are considered to be at risk of producing outburst floods that could cause loss of life and damage to property in the downstream areas.

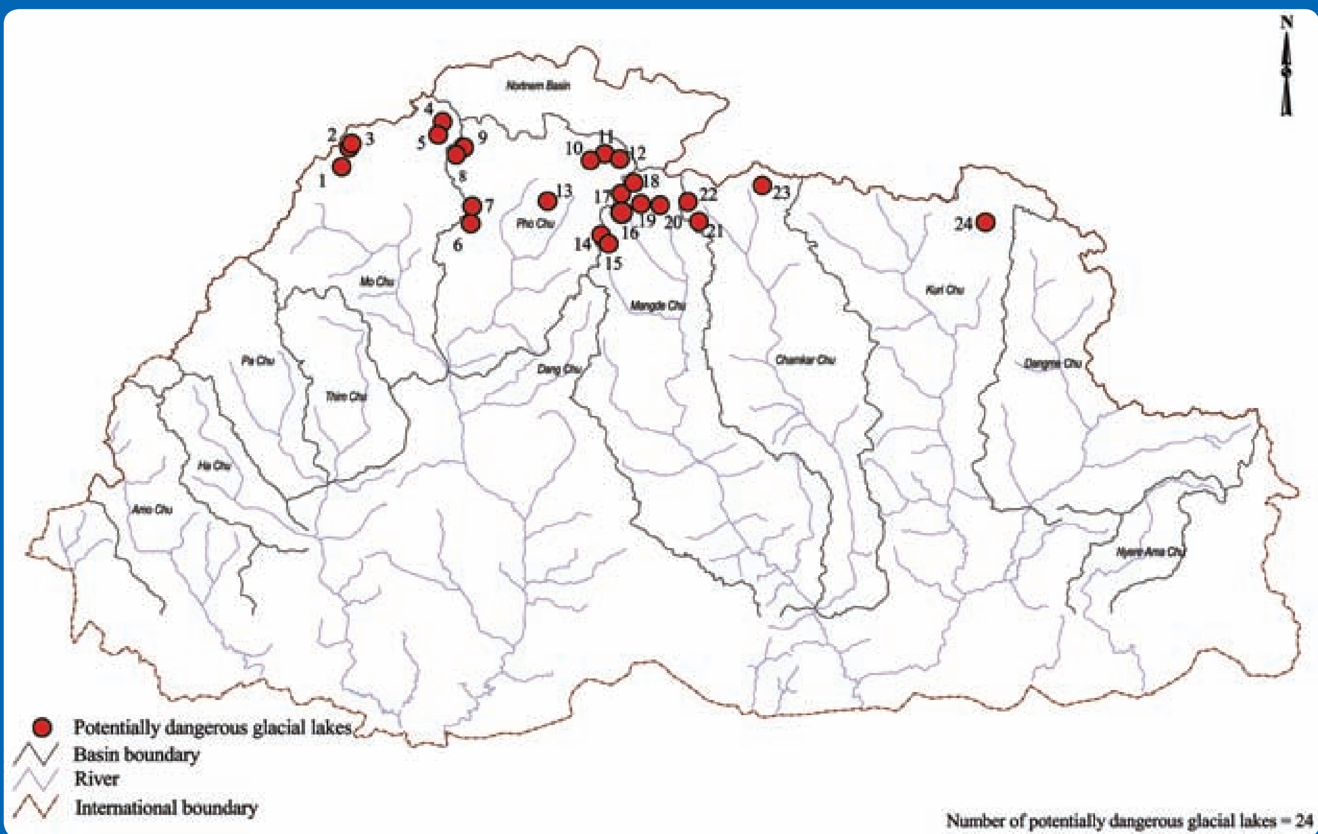
Glacial lakes of Bhutan

The inventory survey in Bhutan was undertaken in 2001 (Mool et al. 2001b). The inventory used the 1:50,000 scale topographical survey maps published between the 1950s and the 1970s by the Survey of India, together with Land Observation Satellite (LANDSAT) Thematic Mapper (TM) images on a scale comparable to the topographical maps. A total of 677 individual glaciers were identified (total area approximately 1,317 sq.km), and 2,674 glacial lakes, of which 24 were classified as potentially dangerous (Table 2 and Annex, Table A1; Figure 3). The great majority of lakes were very small. Glacial lakes with an area of more than 0.02 sq.km and in contact with, or close to, the main glacier, together with other criteria, were analysed to estimate potential risk. Several larger than 1.0 sq.km were immediately classed as potentially dangerous.

Several years prior to the inventory, on 7 October 1994, a glacial lake outburst flood occurred from Luggye Tsho in the watershed 90 kilometres upstream of Punakha Dzong in Bhutan. The resulting deluge along the Pho Chhu River caused extensive material damage and some loss of life. At the time there was little public awareness of the potential dangers from GLOFs. Nevertheless, the Royal Government of Bhutan sent several teams to the area: efforts were made to mitigate the losses and steps were taken to investigate the glaciers and several associated lakes. The level of Raphstreng Tsho was lowered using extensive manual labour, although it was realised that there remained the prospect of subsequent outbursts from the same group of glaciers. Assessment of available documents and news media reports by Watanabe in 1995 added considerably to knowledge about the degree of stability of several of the larger glacial lakes in Bhutan (Watanabe and Rothacher 1996).

Preparation of an updated inventory of major glacial lakes and assessment of glacial lake outburst flood potential in Bhutan, including ranking of potentially unstable glacial lakes, was also undertaken during the Japan-Bhutan Joint Research of 1998. Thirty glacial lakes were recorded and full inventory sheets were prepared. Risk assessments were made for future monitoring (Ageta and Iwata 1999).

Figure 3: **Location of glacial lakes that were considered to be potentially dangerous in Bhutan in the 2001 inventory** (for details of lakes see Annex, Table A1)



Source: Mool et al. (2001)

Based on a study of 66 glaciers from the topographic maps of 1963 and satellite images of 1993, Karma et al. (2003) reported that glacier retreat had averaged 8.1% in the Bhutan Himalaya over this period. In 1963, the area covered by glaciers was 146.9 sq km; by 1993, this had been reduced to 134.9 sq.km. Later, based upon assessment of accelerated ice melt, gentle gradient at the snout region, eroding left lateral moraine ridge by discharge water from Luggye lake further upstream, and many seepages from the left lateral moraine, Karma et al. (2008) concluded that the growing Thorthormi glacial lake had a potential for outburst in the near future. This supplemented the previous work of Gansser (1966), Watanabe and Rothacher (1995), Häusler et al. (2000), and Richardson and Reynolds (2000). At present, there are 25 lakes in Bhutan identified as potentially dangerous and warranting further investigation.

Glacial lakes in the Ganges Basin within China

The present report focuses on the four Himalayan countries of Bhutan, India, Nepal, and Pakistan. However, glacial lake outbursts can have transboundary impacts (Figure 1 and Table 1), thus a brief description of the glacial lakes of the Ganges river basin lying within the Tibet Autonomous Region (TAR) of China is also relevant. An inventory study was conducted by ICIMOD jointly with the Cold and Arid Regions Environmental and Engineering Research Institute/Chinese Academy of Sciences (CAREERI/CAS) and the Bureau of Hydrology Tibet, China, to map the glaciers and glacial lakes in eight sub-basins of the Ganges basin within the Tibet Autonomous Region of the PR China (Daoliqu, Jiazhangangge, Jilongcangbu, Majiacangbu, Poiqu, Pumqu, Rongxer, and Zangbuqin basins). Altogether 824 lakes covering an area of 85.19 sq.km were identified, of which 77 were categorised as potentially dangerous (Table 2) (Wu Lizong et al. 2005).

Glacial lakes of India

Himachal Pradesh

In 2004, the CSK Himachal Pradesh Agricultural University (CSKHPAU) collaborated with ICIMOD to prepare an inventory of glaciers and glacial lakes in the Himachal Pradesh (HP) Himalayas. The study identified 2,554 glaciers with a total area of 4,161 sq.km. Using remote sensing techniques, 156 glacial lakes were identified with a total area of 385 sq.km, of which 16 were considered potentially dangerous (Table 2 and Annex Table A2) (Bhagat et al. 2004).

Uttaranchal (Uttarakhand)

In 2004/05, the Wadia Institute of Himalayan Geology (WIHG) and ICIMOD collaborated to produce an inventory of glaciers and glacial lakes for the State of Uttaranchal (Uttarakhand). The study identified 1,439 glaciers with a total area of 4,060 sq.km, and 127 glacial lakes with a total area of approximately 2.5 sq km. Most were very small and none were identified as potentially dangerous (Table 2) (Sah et al. 2005).

Tista River Basin, Sikkim

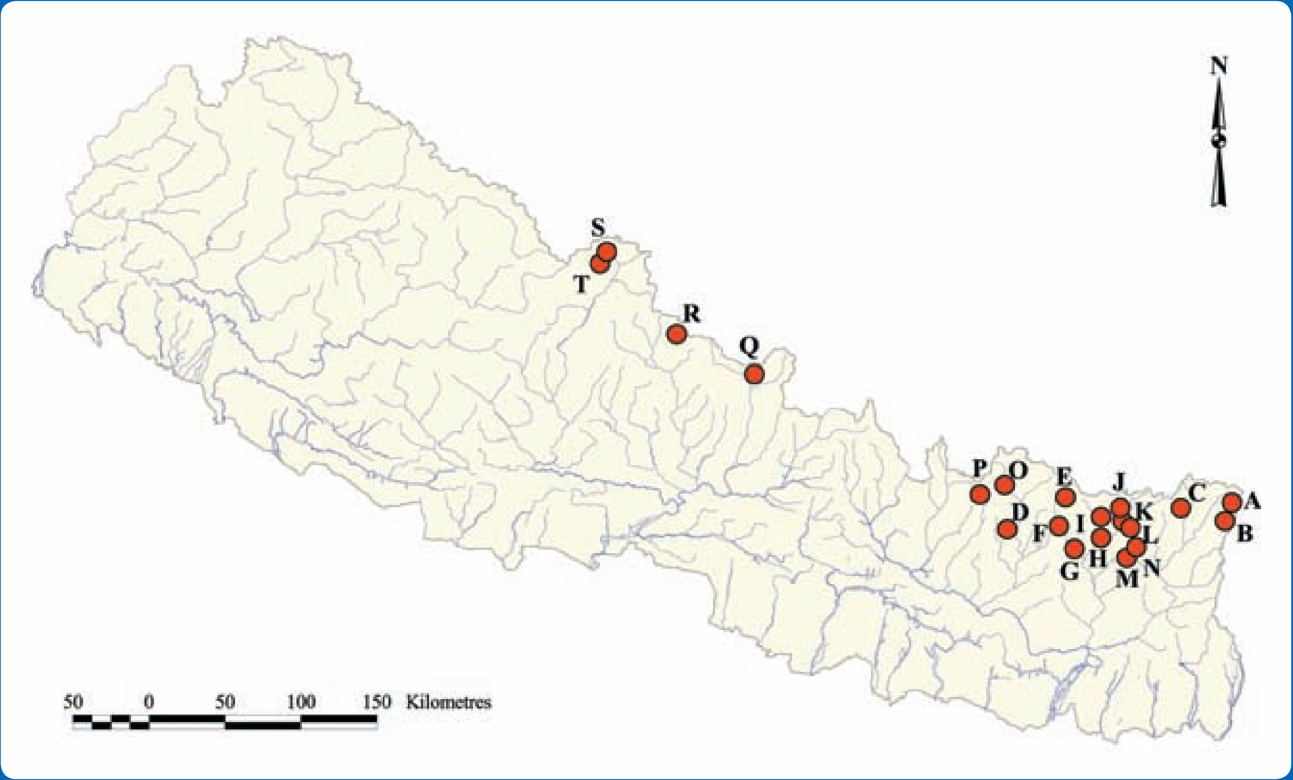
In 2003, ICIMOD, extended the inventory to the Tista river basin in the Sikkim Himalayas, India. This study identified 285 glaciers with a total area of 577 sq.km together and 266 glacial lakes, 14 of which were rated as potentially unstable (Table 2 and Annex, Table A3) (Mool et al. 2003).

Glacial lakes of Nepal

The Nepal inventory was carried out between 1999 and 2001 using topographic maps published by the Survey of India between 1950 and the 1970s (1:63,360) and by the Survey Department, Government of Nepal in 1996 (1:50,000), together with LANDSAT TM, IRS (Indian Remote Sensing)1D LISS3 (Linear Imaging and Self-Scanning Sensor) and some selected SPOT (Système Probatoire d'Observation de la Terre/Satellite Pour l'Observation de la Terre) satellite images from between 1984 and 1994. The inventory identified 3,252 glaciers with a total area of 5,324 sq.km, and 2,323 glacial lakes with a total area of about 76 sq.km (Table 2 and Annex, Table A4; Figure 4) (Mool et al. 2001a). The great majority of the lakes were very small and had probably originated in the recent past. Altogether 20 lakes were recorded as potentially unstable and warranting further investigation, including the Tsho Rolpa, Imja, Thulagi, and Lower Barun lakes.

From 2008 through 2009/10, ICIMOD with the support of the World Bank, Sida and the Norwegian Ministry of Foreign Affairs embarked on a revision of the first inventory in a desk-based study using remote sensing data and other information. The study identified 1,466 glacial lakes in Nepal (down from 2323) with a total area of 65 sq.km (down from 76 sq.km), of which 21 were identified as potentially dangerous. The reduction in the number of lakes appeared mainly to reflect

Figure 4: **Location of glacial lakes reported as being potentially dangerous in Nepal in 2001**



Source: Mool et al. (2001)
A = Nagma Pokhari (Tamor); B = (unnamed) (Tamor); C = Lower Barun (Arun); D = Lumding (Dudh Koshi); E = Imja (Dudh Koshi);
F = Tam Pokhari (Dudh Koshi); G = Dudh Pokhari (Dudh Koshi); H = (unnamed) (Dudh Koshi); I = (unnamed) (Dudh Koshi);
J = Hungu (Dudh Koshi); K = East Hungu 1 (Dudh Koshi); L = East Hungu 2 (Dudh Koshi); M = (unnamed) (Dudh Koshi);
N = West Chamjang (Dudh Koshi);O = Dig Tsho (Dudh Koshi); P = Tsho Rolpa (Tama Koshi); Q = (unnamed) (Budhi Gandaki);
R = Thulagi (Marsyangdi); S = (unnamed) (Kali Gandaki); T = (unnamed) (Kali Gandaki)

merging of small lakes; the average lake area increased. The lakes of potential concern were further grouped into three categories: Category I – requiring detailed field investigation and mapping (6), Category 2 – requiring close monitoring with reconnaissance field surveys (4), and Category 3 requiring periodic observation (11) (Annex, Table A5). Five of the 21 lakes were not listed during the inventory study of 2001 as potentially dangerous, and four of the lakes identified in the original study as potentially dangerous were removed from the list (Annex, Tables A4, A5) (ICIMOD 2009, unpublished).

Glacial lakes of Pakistan

In 2005, the Water Resources Research Institute (WRRI) of the Pakistan Agricultural Research Council (PARC) collaborated with ICIMOD to compile an inventory of glaciers and glacial lakes in the Indus basin in Paksiatn, from a series of studies carried out between 2002 and 2005. The study identified a total of 5,218 glaciers with an area of 15,041 sq.km, and 2,420 glacial lakes, 52 of which were considered potentially dangerous (Table 2 and Annex, Table A6) (Roohi et al. 2005). The upper Indus basin and its tributaries, covering parts of the Karakorum, Hindu Kush, and Himalayas, is estimated, with input from seasonal snowmelt and glacier melt, to provide about half of the entire flow of the Indus River.

Total glaciers and glacial lakes in the Hindu Kush-Himalayan region

The inventory studies in the five Hindu Kush-Himalayan countries of Bhutan, China, India, Nepal, and Pakistan, identified a total of 15,003 glaciers, covering an area of about 33,344 sq.km, and 8,790 glacial lakes, of which 203 were identified as potentially dangerous (Table 2) or 204 with the addition of Thorthormi glacial lake in Bhutan. The inventory still does not cover the Himalayan areas of Arunachal Pradesh and Jammu and Kashmir in India, Afghanistan, or Myanmar; thus the numbers for the whole of the Hindu Kush-Himalayan region will be higher.

Extra-regional involvement

Interest in glacial lakes in the region increased as the potential for serious downstream damage became more widely discussed. Several international agencies continued or expanded their support for the ICIMOD activity (CIDA, JICA, UNEP). At the same time, several institutions and individual university groups from outside the region became involved, or extended earlier investigations in the Nepal and Bhutan Himalaya and northern Pakistan. There has been a heavy focus of interest on the Imja glacier and lake (Imja Tsho) and Tsho Rolpa in Nepal, as well as investigations of glacial lakes in the Bhutan Himalaya (e.g., Watanabe and Rothacher, 1996; Häusler and Leber, 1998). Many non-regional institutions, such as Hokkaido, Nagoya, and Tokyo Universities in Japan, under the Glaciological Expedition to Nepal (GEN) (Yamada 1998a, 1998b), studied glacial lakes in Nepal and Bhutan. The National Data Center for Snow and Ice, University of Colorado/ NASA, USA is archiving data on glaciers under a GLIMS (Global Land Ice Measurements from Space) project. Institutions from the UK, such as Aberystwyth University and Reynolds Geo-Sciences Ltd., and from Germany, studied glacial lakes in Nepal and Bhutan, including Tsho Rolpa (Richardson and Reynolds 2000) and Thulagi (Hanisch et al. 1998). Kennneth Hewitt and his team from the Cold Regions Research Centre, Wilfrid Laurier University, Ontario, Canada, carried out various field investigations in the Karakorum in Pakistan from the 1960s onwards (Hewitt 1982, 2009). The University of Vienna carried out studies of glacial lakes in Bhutan for possible mitigation activities (Häusler and Leber 1998; Häusler et al. 2000). Vrije Universiteit, Amsterdam, carried out an engineering and geomorphological analysis of the moraine dam of Tsho Rolpa glacial lake in the Nepal Himalaya (Modder and Olden 1996).

Other examples include basic studies for assessing the impact of climate warming on the Himalayan cryosphere, with field work in the Nepal Himalaya and on the Tibetan Plateau, conducted between1994 and 1996 by the Institute of Hydrospheric-Atmospheric Sciences, Nagoya University, Japan; the Department of Hydrology and Meteorology, Ministry of Science and Technology, Nepal; and the Lanzhou Institute of Glaciology and Geocryology, Chinese Academy of Sciences (Nakawo et al. 1997); a project between 1997 and 1999 to study the rapid shrinkage of summer-accumulation type glaciers in the Nepal and Bhutan Himalaya (Ageta et al. 2001); and a computer-aided study on the rapid shrinkage of glaciers conducted between1998 and 2000 (Naito et al. 2000). Many of the above studies were carried out under 'Cryosphere Research in the Himalayas' (CREH) supported by the Grant in Aid for Scientific Research Programme from the Japanese Ministry of Education, Science, Sports and Culture.

3 Early Warning Systems, Monitoring, and GLOF Mitigation

Identification of potentially dangerous glacial lakes and recognition of risks associated with them, including ranking of the critical lakes, has become a priority task. Once the critical lakes are identified, the planners, developers, and scientists involved need to develop and implement appropriate measures to reduce the potential risks from these lakes. Measures include: monitoring, to provide an early indication of changes; early warning systems, to provide downstream residents and owners of infrastructure time to take avoidance action; and mitigation measures, to physically change the situation and thus reduce the risk.

Monitoring and early warning systems

The United Nations International Strategy for Disaster Reduction (UNISDR), in a 2006 report, defines early warning as "the provision of timely and effective information, through identified institutions, that allows individuals exposed to a hazard to take action to avoid or reduce their risk and prepare for effective response" (United Nations 2006).

Effective GLOF monitoring and early warning systems are an important part of disaster preparedness; they have the potential to greatly reduce loss of life and property. Any such system should involve application of remote sensing tools, such as the universally available earth observation satellite data, over-flight reconnaissance with small format cameras, telecommunication, and broadcasting systems.

Much progress has already been made in this area, particularly in Nepal and Bhutan. The National Action Plan for Adaptation (NAPA) to Climate Change prepared by the Royal Government of Bhutan has placed considerable emphasis on GLOF vulnerability reduction efforts. Similarly, the Government of India has brought out a 'National Communication on Climate Change Mitigation and Adaptation' which has also pinpointed GLOF vulnerability reduction efforts. However the results are not always without problems. Some examples of early warning systems are given in the following.

Early warning system in the Sutlej river basin, India

Some measures have been put in place in the Sutlej River basin for monitoring, forecasting, and early warning to deal with flash floods, especially from cloudbursts. As GLOFs are one of the causative factors in propagating flash floods downstream, these measures also act as an early warning system for a GLOF. Telemetry stations set up by the Snow and Hydrology Division of the Central Water Commission in Sumdo, at the confluence of the Parechu and Spiti rivers, and Khaab, at the confluence of the Spiti and Sutlej rivers, and by the Naptha-Jhakri project at Dubling, are intended to monitor any increase in the water level and to relay information. They were introduced in response to the gap in early warning that was felt after the floods in 2000, and also for the protection of hydropower projects. Similarly, a wireless network at Reckong Peo, used by security personnel with connections to border outposts, and the Doordarshan Satellite Earth Station and All India Radio Relay Centre, have been very useful in generating warnings and in communicating during emergencies (UNDP 2008).

Early warning system in the Tsho Rolpa and Tamakoshi valleys, Nepal

Lake Tsho Rolpa in the Tamakoshi sub-basin in eastern Nepal is fed by Trakarding glacier and is one of a small number of glacial lakes that have been studied in detail, including field investigations of the lake itself and the downstream area. This investigation led to a realisation in the 1990s that the risk associated with the lake, whose level had risen to the crest of its containing end moraine dam, was potentially serious (WECS 1993, 1994). It was feared that Rolwaling valley downstream of the lake could be inundated due to catastrophic outflow and that widespread loss of life and serious damage to local infrastructure, including potential damage to the 60 MW Khimti Hydroelectric Project, was a high probability (Reynolds1999).

Attempts to significantly reduce the risk of a GLOF occurring from Tsho Rolpa have been extensively documented. Although the early warning system(s) was initially to some extent successful, a serious problem arose as a result of interference from local people. Details of the early warning systems are given below.

The early warning systems

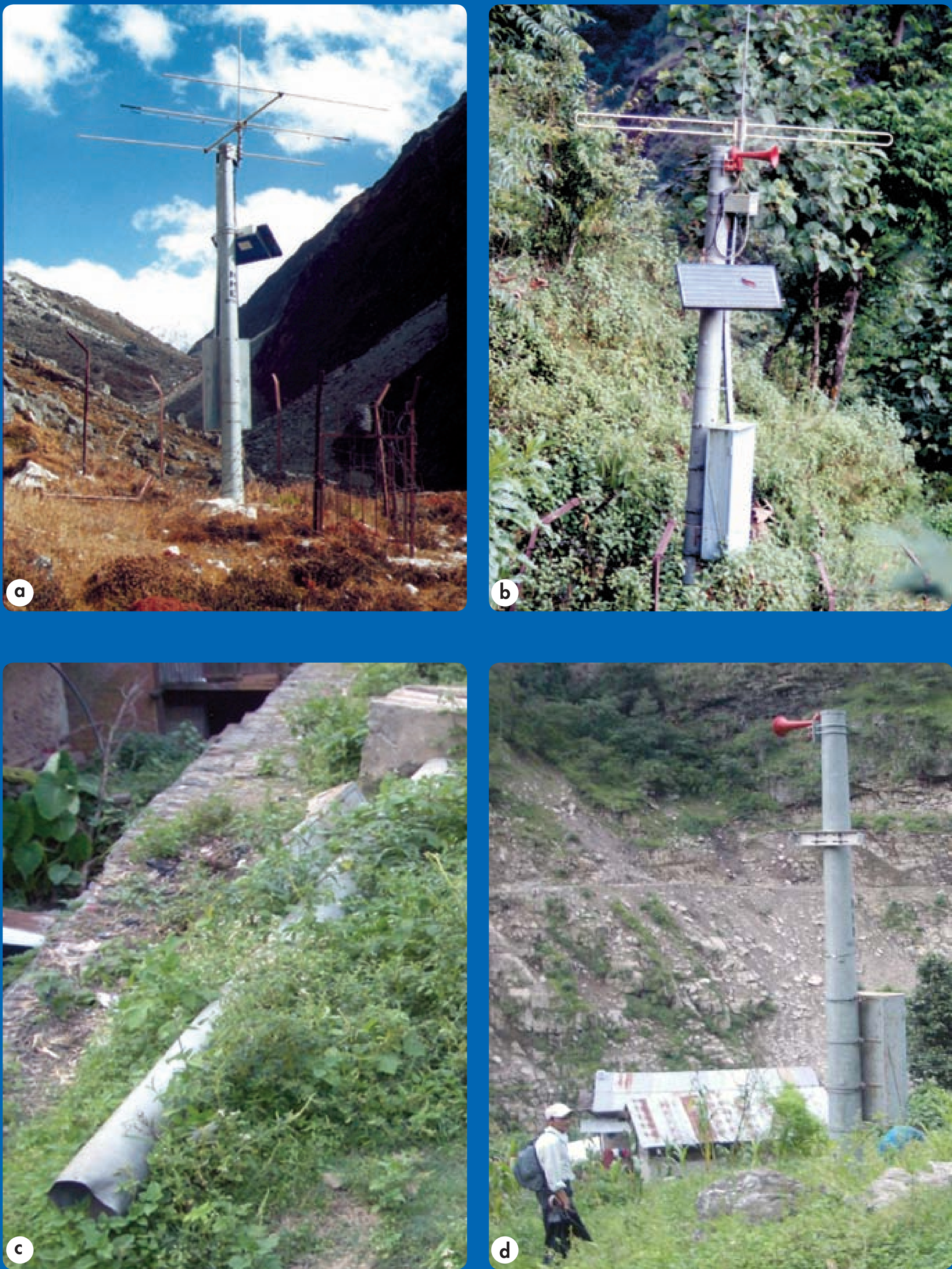
An intensive warning system is needed during short periods when construction projects are underway or for other reasons when a significant risk is identified. In June 1997, a manual early warning system was installed by the Nepal Government as an emergency measure for the local villagers and the Khimti Hydropower Project, under construction at that time. The emergency measure was needed in view of the rapid rate of deterioration of the moraine dam, and the construction activities of the Tsho Rolpa GLOF Risk Reduction Project (TRGRRP) which aimed to lower the lake level (see next section). Early warning systems were installed in the Rolwaling and Tamakoshi valleys. Army camps were established at the terminal moraine and at Naa village, the nearest village to the lake. Police posts were also established at Naa and Bedding villages. Each army camp and police post was provided with a high frequency radio transceiver; the army post at Naa also had a backup set. The police posts and the army camp in Naa were in regular radio contact with their respective headquarters in Kathmandu. The army posts were also provided with satellite telephones. The lakeside army post used one of the phones to contact the Disaster Prevention Cell at the Home Ministry twice a day to deliver status reports. In the event of a GLOF, Radio Nepal, the national broadcaster, would broadcast a warning (Reynolds, 1999; Bajracharya, et al., 2007).

In January 1998, MeteorComm and its partner, British Columbia Hydro International Ltd. (BCHIL) of Vancouver, signed a contract with the Government of Nepal, Department of Hydrology and Meteorology (DHM), to design, supply, install and commission an audible warning system downstream of Tsho Rolpa (www.MeteorComm – Wireless Communications Tsho Rolpa.mht). The project was financed by the World Bank (WB) at a total cost of US $ 1,032,000. This first early warning system installed at Tsho Rolpa and the villages of the Tamakoshi valley in May 1998 was intended to warn people living in downstream areas in the case of a GLOF event, and consisted of a GLOF sensing and warning system. The sensors would detect the occurrence of a GLOF and transmit relevant information to the transmitter station thus setting in motion the warning process. The warning would sound to alert the local people downstream. This system was fully automated and required no human intervention.

The GLOF sensing system consisted of six water level sensors installed along the right bank of the river channel immediately downstream of the lake outlet at Sangma Kharka; this was designed to detect the onset of a breach. Three sensors were connected by armoured and shielded cables to each of the two independently functioning transmitting stations (Figure 5a) located at a higher elevation and within 80 m of the sensors. Each sensor was located at a different elevation above the previous high water mark such that different sensors would be able to indicate any progressively rising river stages. Thus, the sensing system would detect the occurrence of a GLOF immediately and signal directly to all warning stations located downstream within two minutes of initiation of a flood. The remote station at Naa village had the dual function of forming part of the GLOF sensing system and providing local warning to the village residents.

The warning system consisted of 19 warning and relay stations installed at the 17 villages of the Rolwaling and Tamakoshi valleys (Figure 5b). The warning stations located in the villages had Meteor Communication Corporation (MCC) 545-transceiver units mounted on 4.67m self-supporting standard galvanised iron power poles. The antennae were mounted on extensions to the poles approximately 5 m above the ground. Lightning rods and solar panels were mounted on the same poles. MCC 545 units, with battery and relay for the horns, were mounted inside sheet metal boxes with lockable shelters, also attached to the poles. All cables were protected by plastic conduits, covered by galvanised sheet metal and strapped to the poles. Air-powered horns, designed to operate off charged air cylinders for a period of two minutes, with a reserve for an additional one to two minutes, were also mounted on the poles. The air horns could provide a sound of 80 dB up to a minimum distance of 150 m under the most adverse conditions. They were backed up by electric horns which could operate for four minutes. The GLOF warning systems were based on 'extended line of sight' (ELOS) VHF radio technology. The warning signal would be transmitted via ELOS ground wave signals from remote station to remote station down the valley. Thus, an early warning signal would be triggered automatically if a GLOF was detected.

Figure 5: **The Tsho Rolpa/Tamakoshi valley early warning system:** a) Sangma Kharka transmitter station outside lake Tsho Rolpa receives signals from sensors and transmits to other remote warning stations; b) the warning and relay station Gongar village, comprising solar panel, battery, antenna and amplifier with siren; c) destroyed siren pole at Sigati village; d) damaged siren at Bhorle village



A second component of the system was the installation of an MCC meteor burst master station located in Dhangarhi, western Nepal. A meteor burst station uses the ionised trails of meteors to extend the range of transmitted radio signals to over 1,600 kilometres (1000 miles). Several of the warning stations, as well as a sensing station, were designed to transmit and receive signals from the master station, to provide further redundancy to the system. The master station also monitored the status of the entire warning system. Thus, the master station provided a communication link between remote stations located in the Rolwaling and Tamakoshi valleys and the monitoring station in Kathmandu.

The outcome

By 2002, four years after establishment, the early warning system was no longer operating (Figures 5c,d) despite the fact that it was a robust system commissioned with the latest technology. Lack of participation by the local communities and disruption of communications during Nepal's long period of political uncertainty, appears to have led to the system being ignored and then destroyed, with components being taken to use for other purposes locally. The people in the area thought that the lake had been reduced to a safe level and lost interest in the warning system. The tendency towards ignoring the importance of early warning was further intensified by the incidence of false alarms (Khanal et al. 2009).

Early warning system in the Upper Bhote Koshi, Nepal

Another example of an early warning system, similar to that of Tsho Rolpa, is in place in the Upper Bhote Koshi valley of eastern Nepal. The system was installed in 2001, mainly for the Upper Bhote Koshi Hydroelectric Project. It consists of two remote sensing stations with data loggers near the Friendship Bridge at the Nepal-China border that are designed to receive, analyse, and transmit data from sensors. If the water level increases significantly, the system will transmit warning signals to stations located at the intake and the powerhouse site of the power station. In this system, there are seven GLOF detection sensors at the Friendship Bridge, one ultrasonic water level measuring device, and six float type water level switches. It operates on short-burst VHF radio signals using meteor burst technology. Warning sirens are set off from compressed air horns which transmit a sound of 127 dB at a minimum distance of 33 m. There are five such stations along the river (Bajracharya et al. 2007), but the early warning system is only installed up to the border between Nepal and China. From there, there is only 6 minutes of warning time down to the Bhote Koshi hydropower station. To be really useful, the early warning system would need to be extended further upstream into China (TAR). As of 2009, the system was still fully functioning – presumably because of the interest of the hydropower project.

Poiqu basin (Sunkoshi – Bhote Koshi basin)

The inventory by Mool et al. (2005) indicated that the number of lakes in the Poiqu basin, TAR, China (Sunkoshi – Bhote Koshi basin), increased from 119 in the 1980s to 139 in 2000, with an increase of 22% in lake area. Nine potentially dangerous lakes were identified from analysis of multi-temporal satellite images and use of GIS tools, based on different criteria. It was recommended that the lakes be monitored regularly and detailed field studies undertaken. Ten sites were selected for installation of early warning systems, some located in Nepal. As of 2009, no systems have been installed.

Monitoring of Imja lake in the Everest region, Nepal

Imja glacial lake has been one of the fastest growing lakes in the Himalayas and ICIMOD has been monitoring the lake as a basis for devising an early warning system. A remote sensing system (using geo-ICT tools and techniques) was developed in cooperation with the Department of National Parks and Wildlife Conservation (DNPWC) and Keio University of Japan (Bajracharya 2009). Two monitoring devices or field servers – the Internet field observation robot (Figures 6a,b) – were installed on the lake shore at 5,000 masl and close to the nearest big settlement, Namche Bazaar, in 2007 by a team led by Keio University, with other researchers from the National Agricultural Research Centre, Japan. It was connected to the Internet in collaboration with the Asia Pacific Advanced Network (APAN) and Nepal Research and Education Network (NREN). The field servers capture time lapse images of the lake and Namche Bazaar (Figures 6c, d) and meteorological data. These are transferred in real-time by Wi-Fi to a server located in Japan at http://fsds.dc.affrc.go.jp/data4/Himalayan/ (Asia Disaster Report 2007).

The World Wildlife Fund (WWF) – Nepal is also conducting a climate change impact assessment of the Everest region, especially Imja Tsho and downstream areas. In partnership with the Department of Hydrology and Meteorology, a simulation has been made of an Imja Tsho GLOF using a dam-break model. A detailed survey of Imja Tsho, and hazard mapping for

Figure 6: **Monitoring of Imja glacial lake:** a) field server the lake (2009); b) solar panel for field server (2009); c) part of image from field server at lake (26 June 2009); d) part of image from field server at Namche Bazar (1 Jan 2010)

communities at risk related to rockfalls and landslides, are also planned. The Information Centre established by WWF Nepal at Ghat, near Lukla provides relevant information.

ICIMOD carried out GLOF simulation studies for Dig Tsho and Imja Tsho in Nepal, and Lunana lake in Bhutan (Bajracharya et al. 2007), and GLOF modelling studies including socioeconomic vulnerability assessments for Zangzangbo, Imja, Tsho Rolpa, and Thulagi lakes in their downstream areas in 2009 (Khanal et al. 2009, unpublished report).The studies provide a basis for ascertaining the arrangements that would be needed for setting up early warning systems in the valleys. A good first approximation was made for land and settlement classification according to four defined levels of risk. This facilitated an estimate of potential losses that can be anticipated in the event of a worst case GLOF occurrence.

Early warning system in the Lunana region, Bhutan

The Lunana area at the head of the Pho Chhu River in west-central Bhutan has been of considerable concern to the Bhutanese authorities. The Luggye Tsho GLOF of 7 October1994 caused heavy damage to the Dzong at Punakha and 23 deaths (Richardson and Reynolds 2000).

A manually-operated early warning system has been placed in the Lunana region by the Flood Warning Section (FWS) of the Department of Energy (DoE). Two staff members from the FWS are stationed in the Lunana lake area. They are equipped with wireless sets and satellite telephones to report lake water levels on a regular basis and to issue warnings to downstream inhabitants. Several gauges have also been installed along the main river as well as at the lakes. These are monitored at various stations at different times depending on the distance from the station and base camp. The station is in regular contact with other wireless stations in the downstream areas along the Puna Tsang Chu, including the villages and towns of Punakha, Wangduephodrang, Sunkosh, Khalikhola, and Thimphu (Bajracharya et al. 2007).

The Japan International Cooperation Agency (JICA) and the Gross National Happiness Commission (GNHC) signed an agreement for the study of GLOF phenomena in Bhutan. This aims to build a network for sharing satellite data for research, to complete an inventory of historical glacial lake expansions, to conduct a detailed analysis of hazardous lakes, to assess risk factors and triggers of GLOFs, and to recommend effective countermeasures, such as deployment of early warning systems. The project will also be extended to cover the Mangde Chu basin, and to recommend mitigation measures (Kuensel Online, 11 June 2009).

Mitigation measures

Potential outburst flood hazards can be alleviated by various techniques. The primary objective is to reduce the risk of a flood from the lake. However, coordinated measures to protect life and property in the downstream area must also be undertaken. It is imperative to have monitoring systems in place prior to, during, and after the construction of infrastructure so that settlements in the downstream area are protected against unintentional creation of hazards. Mitigation measures to effect risk reduction can be structural or non-structural. In the following, mainly structural measures are discussed.

The most common structural mitigation measures are aimed at reducing the volume of water in the lake. Reduction of the volume of water in the lake should reduce the potential peak surge discharge as well as the hydrostatic pressure exerted on the moraine dam, and is the most effective mitigation measure. There are different ways to achieve this that can be used alone or in combination:

1. Controlled breaching of the moraine dam
2. Construction of an outlet control structure
3. Pumping or siphoning the water from the lake
4. Tunnelling through the moraine barrier or under an ice dam

Mitigation measures must be brought into play in such a way that no unintentional increase in danger occurs. Since moraine dam stability is a major part of the problem, it follows that artificial disturbance of the dam itself during construction activity could actually increase the degree of danger while mitigation measures are being put into place. Thus, choice of an appropriate method for each individual lake is critical. This necessitates careful evaluation of the lake, glacier, damming materials, and surrounding landscape. Physical monitoring systems for the dam, lake, glacier, and surroundings are necessary at all stages of the mitigation process.

In addition to reducing the volume of lake water, there are other preventative measures around the area that can help reduce the likelihood, or impact of, a GLOF. These include removing masses of unstable rocks to guard against avalanches or rockfalls hitting the lake surface and causing a surge wave, and protecting infrastructure in the downstream area. Engineering work as a part of hazard reduction efforts, especially in such remote and high altitude areas, is very expensive, however.

Some examples of programmes, projects, and interventions related to mitigation measures that have been applied to reduce the impact of GLOF risk in the Himalayan region are described below.

Bhutan

The earliest awareness of glacial lakes in Bhutan dates from the 1960s (Gansser 1966). After the Luggye Tsho GLOF event of 7 October 1994 in Punakha Wangdue valley, emphasis was placed on GLOF risk mitigation. The Royal Government of Bhutan sent an Indo-Bhutan team of experts to the Lunana area in 1995 to investigate any residual risk. The team recommended immediate mitigation measures for Raphstreng Tsho, including an attempt to lower the lake's water level as soon as feasible. Funding was provided by the Government of India with consulting by Water and Power Consultancy Services (India) Ltd (WAPCOS). The original plan was to reduce the lake level by 20 m in the first phase. WAPCOS found that this would actually take seven to eight years, but that lowering of the lake level by only four metres would also significantly reduce the risk of overtopping. Controlled opening of the moraine dam was carried out by manually widening the outlet channel with crowbars, pickaxes, and spades. Although a method of pumping to reduce the lake level was attempted initially, it was discarded as both ineffective and too expensive for such a remote region. Despite numerous constraints, such as having to work with manual tools, and obstructions caused by huge boulders in the channel bed, the water level in the main lake was lowered by 0.95 m, and in the two subsidiary lakes by 0.94 m and 1.5 m, by October 1995 (Häusler and Leber 1998; ICIMOD 2001b). The lowering continued until the lake level was reduced by four metres in 1998 (UNDP-ECHO 2007a).

Phase 2 of the Raphstreng Tsho Outburst Flood Mitigation Project began in 1999 supported by Austro-Bhutanese Cooperation. The main aim was to assess the geo-risks of Raphstreng Tsho and Thorthormi Tsho in the Lunana area. The activities involved fieldwork with an integrated multi-disciplinary approach using remote sensing, geological, hydro-geological, and geophysical methods to interpret the subsurface characteristics of the moraine dam (Häusler et al. 2000; Mool et al. 2001b). The investigations indicated that the risk of an outburst from Raphstreng Tsho was low, but the risk from Thorthormi Tsho was high (Häusler et al. 2000).

Thus a project for 'Reducing climate change-induced risks and vulnerabilities from glacial lake outburst floods in the Punakha-Wangdue and Chamkhar valleys' was initiated by UNDP to run from 2008 to 2012 in conjunction with the Department of Geology and Mines, the Department of Energy (Ministry of Economic Affairs), and the Disaster Management Division (Ministry of Home and Cultural Affairs). The Global Environment Fund (GEF) has provided US$ 3.5 million; the project is mainly examining the effectiveness of structural risk reduction measures. Activities cover risk reduction measures for Thorthormi glacial lake, including artificial lowering; hazard zonation mapping in

"Installing an automatic early warning system (EWS) to reduce the impact of a glacial lake outburst flood (GLOF) in the Punatshangchu basin has become urgent, according to participants of an inception workshop on the regional climate risk reduction project in Punakha. The plan to establish an automatic EWS has not taken off yet, although the government in early 2009 said that automatic sirens would be set up in the villages down from the Lunana area, which would warn people at the first hint of any impending floods in the area. The earlier plan was to install an automatic sensor a few kilometers upstream of Phochu to detect the first flood and five sirens along the area……. . To make EWS comprehensive, there will now be two sensors at two locations: one at Lunana and the other 25-30 km upstream of the Phochu. United Nations Development Programme's (UNDP) Kinley Penjor said UNDP would develop a soft package to prepare or train people in the valleys to make EWS effective. He said 'after the machinery is in place, it's important for people to know what to do and how to respond to climate induced GLOF.' " (Kuensel Online 18 Jan 2010)

Chamkar chu in Bumthang; and the expansion of an early warning system along the Punakha-Wangdue valley. In addition, there are plans for improvement of national, regional, and local capacities to avert climate change-induced disaster in the Punakha-Wangdue and Chamkhar valleys. The project should demonstrate practical measures to reduce the risks associated with the Thorthormi glacial lake and facilitate replication of the lessons learned in other high-risk areas, both within and outside Bhutan (Kuensel Online, 7 December 2009; www.managingclimaterisk.org).

Proposals have also been made for Samdingkha to have a siren tower, given its high vulnerability to GLOFs. Two possible locations were identified: Siren 1 below Lorina village on the right side of Pho Chu facing Samdingha and about 60 m from the river level; and Siren 2, about 200 m above the suspension bridge. Both locations provide a good view of the vulnerable areas.

A GLOF hazard zonation plan for the Puna Tshang Chu valley from Khuruthang in Punakha to Kalikhola Lhamoyzinkha is among various risk management measures the Department of Geology and Mines (DGM) has prepared with the Netherlands Climate Assistance Programme (NCAP) (Karma et al. 2008; Kuensel Online 7 December 2009).

Nepal

The Tsho Rolpa Mitigation and Early Warning Programme was the first glacial lake outburst flood operation to include civil engineering structures in the entire HKH region. The early warning measures are described in some detail above. The preliminary investigation of Tsho Rolpa and its downstream section of the Rolwaling valley was undertaken by WECS in 1993 (WECS, 1993, 1994; Mool, 1995). Investigations in subsequent years led to a recommendation for immediate action, as well as for long-term measures. As an immediate measure, Wavin Overseas B.V., Holland, installed siphons over part of the terminal moraine in May 1995. This was primarily to test the use of siphons at high altitude. The project was undertaken in cooperation with the Netherlands-Nepal Friendship Association. The siphon system consisted of three inlet pipes submerged in the lake and connected to a single pipe with a discharge outlet located at a stable part of the outer flank of the moraine. Though the test siphons were installed successfully, the induced outflow was far below that required to ensure reducing the lake level by the targeted three metres, and it appeared that they might never exceed inflow of additional glacier and snow melt.

In the second phase of the mitigation measures, supported by a contribution of $2.9 million from the Dutch Government, an open channel was cut through the moraine dam and a four-metre deep artificial spillway succeeded in lowering the lake level by three metres. The spillway construction was completed by the Tsho Rolpa GLOF Risk Reduction Project of the Department of Hydrology and Meteorology in June 2000.

Pakistan

The high altitude, fragile environment, and isolated nature of Pakistan's Northern Areas poses special constraints and challenges for mitigating natural hazards such as glacial lake outburst floods.

The glacial lakes in this area are predominantly ice-dammed lakes resulting from local glaciers that have thickened and advanced in recent decades (Hewitt 2009). They must be differentiated from the supra-glacial and moraine-dammed lakes that are the principal concern of this report. Five GLOF events were reported during the first half of 2008 in the Gojal area of the Hunza valley and substantial damage to infrastructure and arable land was reported due to GLOF events in association with the Ghulkin and Passu glaciers. There is no regular early warning system in the Hunza river basin, and the local people use traditional methods, such as lighting torches and firing weapons, to warn the villagers of flash floods.

Risk reduction measures taken in Gojal include excavation, channelling, and spillway development. (UNDP-ECHO 2007b). A local village community used a siphoning technique to drain the lake associated with the Ghulkin glacier and reduce the threat posed by a potential outburst flood. A lateral moraine was excavated to set up the siphon (Roohi et al. 2008).

4 Remote Sensing and GLOF Risk Assessment

Introduction

Remote sensing of glaciers began with terrestrial and aerial photography during the mid 20th century. The Landsat Multispectral Scanner (MSS) was one of the first satellite data systems used for glacier mapping by the United States Geological Survey (USGS) in the early 1970s. Since then, satellite data from different sensors have been used as soon as they became available. Today the discipline embraces a large variety of data types from laser scanner data to very high resolution satellite imagery that can be applied to the mapping of changes in area or surface zonation of glaciers. Recent development in satellite sensors (higher spatial and spectral resolution) and better image processing software (advanced classification techniques) has made an algorithm-based semi-automated classification approach possible.

Use of statistical and remote sensing-based approaches has proved an important addition to the earlier deterministic, return period, and qualitative geomorphic analyses. Such tools have been used, for example, to investigate the probability of catastrophic drainage of moraine-dammed lakes in southwestern British Columbia, Canada (McKillop and Clague 2007). Glacial lake hazard assessment has been undertaken in the Swiss Alps using three scale levels of remote sensing with a progressive focus on critical glacial lakes (Huggel et al. 2002). In very remote regions, such as the Cordillera Carabaya in the Peruvian Andes, remote sensing has proven to be of great value, being virtually the only tool available to fill gaps in information (Huggel et al. 2003).

In the Hindu Kush-Himalayas, remote sensing methods using space borne imagery with or without aerial photographs and in situ field surveys, have been widely applied for the assessment of glaciers and glacial lake hazards by different researchers (Yamada 1998a, 1998b; Reynolds 1998; Mool et al. 2001a, 2001b; Huggel et al. 2002; Bolch et al. 2008; Fujita et al. 2009; Watanabe et al. 2009). The appropriateness of different types of data for use in GLOF risk assessment, their use in developing a new and more accurate inventory of glaciers and glacial lakes for the Hindu Kush-Himalayan region, and application in monitoring are discussed in the following.

Using remote sensing data in GLOF risk assessment

Given the enormous extent and unusually challenging accessibility of the HKH region, application of remote sensing (and continued refinement of methodology) is a fundamental requirement for any assessment of the potentially large scale and widespread hazard posed by the rapid formation of new glacial lakes and the continued enlargement of existing ones. Because of the numbers involved, only a very small percentage of such lakes will ever be visited in the field. This creates the essential challenge.

Before any progress can be made in assessing the magnitude of the problem, however, or in the development of methods to reduce downstream vulnerability or mitigate the effects of glacial lake outbursts, the sources of possible danger must first be identified and precisely located. While many sources of potential danger have already been noted, the entire situation is extremely volatile – new glacial lakes form while existing ones continue to expand. A replicated monitoring system is the first task for long-range application of remote sensing.

Emphasis must be placed on the relatively small number of lakes that can be identified as especially vulnerable to sudden outbreak. This is not only because of the degree of danger to which people and infrastructure may be exposed, but also to ensure the most efficient use of the limited resources available (as already recommended in the early report produced by

WECS in 1987). Glacial lakes must be ranked in order of their apparent level of instability. This process has two aspects: (1) evaluation of the current degree of lake instability from a purely geophysical point of view; and (2) determination of the potential for downstream damage and loss of life in the event of actual lake outburst. The two foci must be examined separately and then combined.

1. Repeat remote sensing of particular glacial lakes is essential. It is clear that priority attention should be given to the larger ones, and/or to those known for various reasons to have enlarged rapidly in recent years and to exhibit other characteristics that suggest instability. The relatively small number of such lakes out of the huge number that were identified by first-pass remote sensing should become candidates for special attention. Nevertheless, this will constitute only a first approximation.
2. It follows that the largest and potentially unstable glacial lakes that are in closest proximity to human activities must be ranked as requiring special attention. Local grazing and cultivation, settlements, and so on, also modern infrastructure, such as hydroelectric facilities, roads and bridges, and popular trekking routes that lead to the various major tourist destinations, must be evaluated.

If lakes, from a purely geophysical/remote sensing survey, are far removed from human activity then, by any definition, they should not be classed as a potential hazard.

Repeated remotely sensed images of high resolution can be used to observe the changes in Himalayan glacial lakes such as expansion mechanisms for monitoring purposes, as shown during the studies of Imja Lake (Fujita et al. 2009; Watanabe et al. 2009). But sole reliance on remote sensing data is inadequate as it cannot furnish the necessary repeat bathymetric information, changes in the height of the damming moraine, or changes in lake level, which are also needed.

Reliable determination of the degree of glacial lake instability, at least in most cases, will require detailed glaciological and geotechnical in situ field investigation. Enough is known about the development of Imja Lake, for example, to conclude that rate of lake expansion alone is not a reliable guide for determination of the degree of instability (Watanabe et al. 2009). That is one reason why it is essential to use remote sensing applications for an initial ranking – to reduce the expense, both in time of available experienced field persons and in cost. Furthermore, highly sensitive remote sensing, utilising the more powerful imagery and software for its examination that is continually becoming available, must be evaluated. Even then, it is unlikely that the need for field investigation will be eliminated.

Selection of appropriate type of remotely-sensed data

Thus the best approach to GLOF risk studies is to use a step-by-step, multi-scale, and multi-level process starting from a regional scale (preliminary reconnaissance) and proceeding to a local scale (detailed information gathering) (Mool et al. 2001a; Huggel et al. 2002). The level of study determines the type of remote sensing data to be used, especially in terms of resolution. Two types of resolution are important: spatial, i.e. distance or area, and temporal, i.e. in time. The spatial resolution of the sensor determines the degree of detail that can be detected, or the smallest size of a feature that can be mapped or sampled. This is categorised in terms of high resolution, medium resolution, low resolution, and very low resolution. The temporal resolution determines variations in size through time – hours, days, months, and so on. There are very few objects and/or phenomena in nature that do not change with respect to one another through the course of time, but the rate of change is different for different phenomena. The temporal resolution has to be in agreement with the rate of hazard development. In other words, changes observed during annual visits of a sensor, for example, might be sufficient to monitor development of a glacial lake, whereas a repeat time of a few days would be necessary for ice avalanches or landslide-induced lakes (Kääb et al. 2005; Bajracharya et al, 2009). Besides the various degrees of resolution, other factors, such as the spatial coverage, i.e., the ground area or width of the ground track sensed, the timing of data acquisition, stereo interferometric or ranging capability, and usability of data, also govern the extent to which remote sensing methods can be successfully applied (Kääb 2005).

The first step in preparing an inventory is to develop a database for a large area. This can be achieved using medium resolution satellite images (e.g., Landsat TM, IRS [Indian Remote Sensing], or ASTER [Advanced Spaceborne Thermal Emission and Reflection Radiometer] images), a digital elevation model (DEM), and ancillary information. Following this, the potentially dangerous lakes can be identified from the inventory data and other defined criteria. At this stage, multi-source data and multi-temporal satellite images are used combined with a DEM (digital elevation model) using GIS tools. The critical (potentially dangerous) lakes can then be ranked, using high resolution images such as IKONOS, QuickBird, or OrbView for detailed local-scale investigations and supporting information related to possible impact on the downstream areas. The last step comprises detailed field investigation leading to assessment of the need for an early warning system and mitigation measures.

Use of remote sensing data for the Himalayan Inventory

ICIMOD, in collaboration with national and international partners, developed the first regional inventory of glaciers and glacial lakes between 1999 and 2005 using various levels of remote sensing, topographic maps, aerial photographs, GIS tools, and satellite images as described in Chapter 2. This first study focused on the Himalayas of Bhutan, India, Nepal, and Pakistan, followed by selected basins in China.

The methodology was based on the guidelines for compilation and assembly of data for the World Glacier Inventory (WGI), developed by the Temporary Technical Secretary (TTS) at the Swiss Federal Institute of Technology (ETH), Zurich in 1977. It involved visual interpretation and manual digitisation of glacier boundaries followed by integration of non-spatial data. The inventory was carried out systematically for the drainage basins on topographic maps. In areas for which there were no topographic maps, satellite images were used. The data represented a wide temporal range and was derived from different map and satellite image sources. Thus the results do not represent a clear comparative picture for a specific point in time. Nevertheless, it provided a necessary first reconnaissance approach (Mool et al. 2001a, 2001b; Bajracharya et al. 2009). This first inventory still had considerable geographic gaps, however, including much of the northeastern Indian Himalaya and Myanmar.

As mentioned above, a new inventory is now being prepared for the whole region, from Afghanistan in the west to Myanmar in the east, based on the principles outlined in the preceding sections. The inventory is being carried out by ICIMOD in conjunction with the Cold and Arid Regions Environmental and Engineering Research Institute (CAREERI) of the Chinese Academy of Sciences (CAS) based in Lanzhou. A similar project, undertaken by the same institutional collaboration, aims to cover the Tibetan Plateau in China. Finalisation of the reports is expected by the end of 2010. This will provide coverage of the entire HKH region and give an authoritative and up-to-date status of glacial lakes. Further firming up of partnership activities will enhance this process. Equally there is a long history of glaciological research in the northwestern regions of the Hindu Kush-Himalayas by 'western' scholars (e.g., Hewitt, Bishop, Schroder, Winiger, and others), in addition to a large contribution by several Japanese scientists, that should be incorporated in the studies. Their continued collaboration should also be encouraged.

The new inventory process

When generating a clear comparative assessment, it is important that the source and source date of the data be as similar as possible. Keeping this in mind, a new rapid methodology has been developed for preparing the inventory of glaciers and glacial lakes that includes generation of a database from a single source with a narrow temporal range.

The readily available data sets are satellite images which are downloadable free of cost, such as Landsat 5 TM, and Landsat 7 TM/ETM+. The scene of a Landsat TM image gives the synoptic view of a land surface area 185 km by 170 km. Landsat TM is a single system which can provide satellite images covering the entire area of the HKH region. The information mapped from Landsat TM images with a spatial resolution of 30 metres pixel size is minimally compatible with a 1:50,000 scale map. However, management of good quality images with single-year coverage of the entire area has proven difficult and it has become necessary to use a wider temporal range, covering a number of years, although much narrower than for the initial inventory. Satellite images (Landsat 5, 7, TM/ETM+) of 2005 ±3 years were selected; they provide the status of glaciers and glacial lakes and baseline information that gives an acceptable range for scientific analysis. In some cases, such as the Myanmar area, images from 2000/2001 had to be used due to limited usability of selected images of 2005 ±3 years.

This new mapping inventory for glaciers is being carried out using a semi-automated approach. Glacier outlines are mapped using multi-spectral (optical) satellite data and 'Definion' software. Parameters were selected based on the 'Guidelines for the compilation of glacier inventory data from digital sources' that were reviewed by several members of the working and user group of 'GlobGlacier' (a global project supported by the European Space Agency to assist global glacier monitoring) and the GLIMS community (Global Land Ice Measurement from Space supported by NASA). The structure of the inventory closely follows the original guidelines of Müller et al. (1977) for the World Glacier Inventory (WGI), and includes the data source and dates of imagery used (Bajracharya et al. 2009).

In contrast to the situation with glacier mapping, there is no global scientific forum concerned with establishing a standard approach to mapping and database development for glacial lakes. For this, ICIMOD has developed its own mapping method and definition of associated information, which will support compilation of a standardised glacier and glacial lake information dataset for the entire HKH region. Briefly the method is as follows. As with glaciers, glacial lake identification and mapping is carried out using a semi-automated approach with satellite images. The same satellite images are used as for the glacier mapping (Landsat 5, 7, TM/ETM+, from 2005±3 years). Glacial lakes are delineated using Arc/GIS and ERDAS Imagine software; Google Earth is used to verify or check lakes in shadow areas. Identification and mapping of water bodies including glacial lakes was found to be easier in the output image of the Normalized Difference Water Index (NDWI, defined as NDWI = [BNIR - BSWIR)/BNIR+BSWIR]) using NIR (near infrared) and SWIR (short wave infrared) bands of Landsat TM or ETM+, thus this method was adopted. There is a limitation in this method as many lakes in the HKH region are snow covered or frozen from November to March, and in some cases it can be difficult to delineate lakes from glaciers. In these cases, lakes are delineated manually as the lake surface is relatively level and smooth compared to the surroundings or glaciers. Post-classification data management and parameterisation is undertaken in a GIS environment. Additional data sets, such as DEM and topographic maps are used to substantiate some important parameters.

This approach provides baseline information for glaciers and glacial lakes. It will also contribute considerably to monitoring studies of snow and ice in the HKH region as the results can be compared, at least to some extent, with those in the first regional inventory. In future, the method can be repeated for later years to provide an exact assessment of change. This new approach to inventory, based on space-borne imagery, will fulfil the need for a mapping method able to deliver data rapidly that is consistent with the established international inventory system. In this way, vital support will be provided for global climate change research and adaptation studies.

Although the data sets are not strictly equivalent, a brief comparison was made between the results of the 2001 inventory for Nepal (based on combination of information from topographic maps that used data compiled from 1950 to the 70s and satellite images from between 1984 and 1994 (see Chapter 2) with the results of the 2009 inventory (using data from satellite images of 2005±3) (ICIMOD 2009b, unpublished report). The total number of glacial lakes decreased from 2,323 in the 2001 study to 1,466 in the 2009 study, with a small decrease in total area from 75.6 sq.km to 64.8 sq.km, and increase in average size (Table 3). Most of the changes appeared to result from the fact that many of the very small supra-glacial lakes mapped during the first inventory had amalgamated to form fewer but larger lakes in the second inventory, while some small lakes had disappeared. Some lakes of mappable size identified in ablation valleys or push moraines in the 2001 study had also disappeared in the later study. Differences in the mapping techniques used, and especially the inconsistent data sources of the first inventory, probably also account for some of the differences identified. Nevertheless, the changes demonstrate the rapidly changing situation, and confirm the need for periodic repeat surveys at set time intervals across the entire region.

The risk assessment process

The basic inventory of glacial lakes over the whole region is Level One in the risk assessment process. Level Two requires identification of those lakes that may pose a potential danger, in other words it assesses the hazard potential of the lakes detected in the images. For this, simple detection of the lakes and lake characteristics must also be complemented by information about the related hazards. In the first inventory, 126 of the 7,966 lakes recorded for Bhutan, India, Nepal, and Pakistan were tagged as potentially dangerous (Table 2). The classification was based on processes and records of past events, geomorphological and geotechnical characteristics of the lakes, lake surroundings, and other physical details (see Chapter 2). Many of the criteria were derived from remotely sensed data, because investigation of a large number of lakes widely distributed over a vast geographic area is inhibitive of field inspection. Geomorphic features and processes are very distinctive on the high spatial resolution satellite images, and aerial photographs and physical parameters of glaciers, glacial lakes, and associated moraines can be estimated easily using stereoscopic views. Use of high spatial resolution satellite images and medium- to large-scale aerial photographs is the best approach available short of detailed field investigation and other forms of evaluation.

Table 3: **Comparison of glacial lakes of Nepal: 2001 survey and 2009 survey[a]**
(ICIMOD unpublished report, 2009b)

Sub basin	Glacial lakes 2001		Glacial lakes 2009		Comparison 2001/2009	
	Number	Area (km²)	Number	Area (km²)	Number (%)	Area (%)
Koshi River Basin						
Tamor	356	7.32	209	6.57	-41.29	-10.22
Arun	109	2.53	81	3.28	-25.69	29.53
Dudh Koshi	473	13.1	243	13. 19	-48.63	0.89
Likhu	14	0.22	13	0.31	-7.14	43.78
Tamakoshi	57	1.26	24	2.15	-57.89	71.07
Sunkoshi	35	0.41	17	0.31	-51.43	-25.73
Indrawati	18	0.28	12	0.11	-33.33	-60.79
Sub-Total	1062	25.1	599	25.92	-43.60	3.30
Gandaki River Basin						
Trishuli	117	2.03	50	1.68	-57.26	-17.44
Budhi Gandaki	37	0.64	12	0.71	-67.57	10.78
Marsyangdi	78	6.28	22	5.16	-71.79	-17.90
Seti	10	0.26	6	0.11	-40.00	-56.54
Kali Gandaki	96	3.29	26	1.88	-72.92	-42.86
Sub-Total	338	12.50	116	9.53	-65.68	-23.73
Karnali River Basin						
Bheri	152	9.16	56	6.94	-63.16	-24.26
Mugu Karnali	280	8.56	218	5.03	-22.14	-41.29
Tila	71	4.97	73	3.58	2.82	-28.01
Humla Karnali	345	13.01	346	12.19	0.29	-6.29
Kawari	44	1.57	24	0.77	-45.45	-50.70
West Seti	15	0.40	25	0.65	66.67	63.00
Sub-Total	907	37.67	742	29.16	-18.19	-22.59
Mahakali Basin						
Mahakali	16	0.38	9	0.137	-43.75	-63.95
Grand Total	**2,323**	**75.64**	**1,466**	**64.75**	**-36.89**	**-14.36**

[a] Note: data for the 2001 survey were derived from topographic maps based on survey data from the 1950s and 60s and satellite images of between 1984 and 1994; data for the 2009 survey were derived from satellite images from 2005±3 (see text)

In the new inventory, image analysis and GIS modelling based on multi-source data such as satellite imagery and digital elevation models (DEM) are applied to derive important parameters for hazard assessment. Slope information is derived from stereo satellite/photo pairs. The Shuttle Radar Transmission Mission (SRTM) DEM from the National Geospatial Intelligence Agency (NGA) and the National Aeronautics and Space Administration (NASA) is used as a base. This DEM maps earth topography using radar signals reflected from the ground at 30 m spatial resolution, although only 90 m data are actually available. In some cases more precise DEMs were used that have recently become available, generated from an imaging instrument flying on Terra Satellite, ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) which has long track stereo capabilities.

Level Three in the risk assessment entails rating or ranking of the potentially dangerous lakes. A detailed approach was developed for the 2009/10 study of the Nepal Himalayas based on factors related to the physical stability of lake surroundings and the moraine dams (i.e., likelihood of failure) , and socioeconomic parameters (i.e., potential impact). The possibly dangerous lakes were first identified from high spatial resolution satellite images and then ranked using detailed study of the images together with other GIS data.

The key parameters applied in the ranking of lakes are changes in boundary conditions of the identified glaciers (frontal retreat and thinning) and lakes (enlargement) over time. Lakes less than 0.02 sq.km in area are not considered dangerous.

The next parameter is the distance between the lake and the glacier and whether or not the two are in contact, close, or less than 1,500 m apart. Lakes more than 1,500 m from the associated glacier are not considered dangerous. The rating of moraines themselves includes height, width and steepness. Steepness is rated as very steep (>45 degrees), steep (25 to 45 degrees), or gentle (<25 degrees). Surroundings of the lake area include factors such as rock or debris slides and hanging glacier avalanche paths.

The socioeconomic parameters include size of settlements (small, <10 houses; medium, 10 to 50 houses; and large, >50 houses); number and type of bridges (wooden, suspension, motorable, and highway bridges); distance from hydropower projects (number and capacity of hydropower projects in megawatts); area of agricultural land; and any other important infrastructure or activities of economic value such as trekking trails, community service centres such as schools and health centres, religious gathering sites, camp sites, and so on. Preliminary information on these parameters was derived from topographic and thematic maps.

The physical parameters were used to identify lakes potentially at risk, and together with the socioeconomic and physical parameters to rank them into categories as follows: 1) lakes requiring detailed field investigation and mapping, 2) lakes which require close monitoring such as reconnaissance field surveys, and 3) lakes where observation is needed over time. This prioritisation is usually a minimum prerequisite before deciding to carry out on-site mitigation measures.

Further investigation is then carried out on lakes identified as Category 1 or 2. This entails application of very high resolution remote sensing data, geophysical studies, and other field work. In the Nepal 2009 inventory case study, six lakes were assessed as Category 1. Detailed field investigations of three lakes, Tsho Rolpa, Imja, and Thulagi, and their moraine dams and surrounding area, were carried out, and the results used for dam-break modelling. Socioeconomic surveys were carried out for the downstream areas (Khanal et al. 2009). The final results, including the updated inventory, are in preparation for publication.

This methodological approach will be extended to other countries in the region as resources become available. In some areas, actual field inspection is likely to prove difficult, if not impossible. More detailed information for these parts can be obtained through intensive application of a variety of specialised methods (especially remote sensing and GIS) by the institutions responsible for the individual regional sections.

The approach can be used to obtain a comprehensive GLOF risk assessment in a time- and cost-effective manner through the application of space technology in combination with other tools. The space- and airborne techniques have limitations with regard to depth penetration; ground-based geophysical surveys such as bathymetric and borehole surveys are needed for below-surface investigation. Remote sensing techniques cannot replace specific ground-based site investigation or individual lake investigation, but space-borne and/or air-borne images are inexpensive and easily accessible sources of data that can be used to identify the very few lakes for which field surveys, which are both expensive and difficult, are needed.

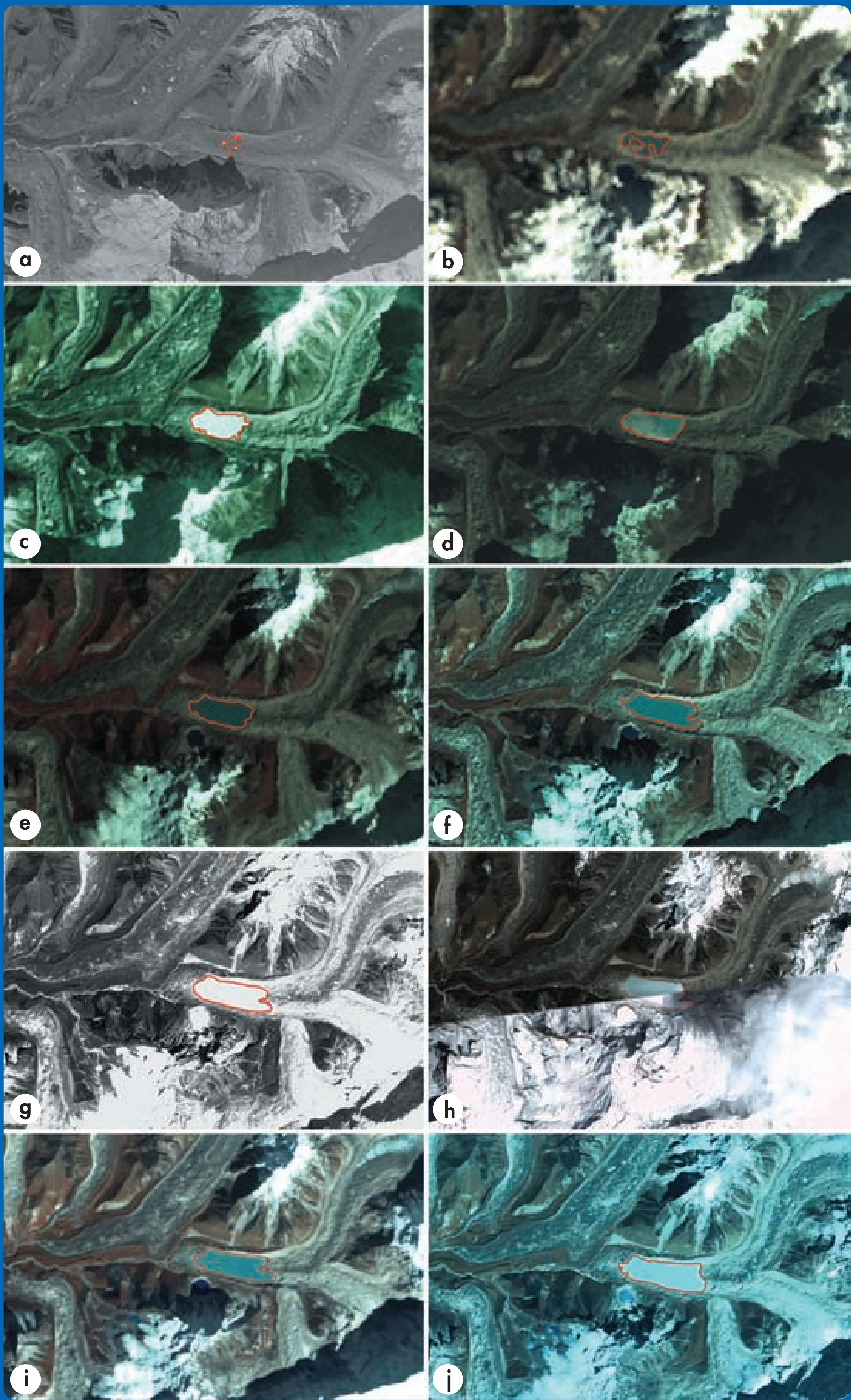
Remote sensing for GLOF risk monitoring

Glacial lakes are still being created and many that exist continue to grow. The formation and growth of lakes need to be monitored on a routine basis to determine possible instability and potential threats to downstream communities and infrastructure. Such monitoring, combined with measurement of the distribution and temporal variation of snow cover using satellite imagery, is essential for GLOF risk assessment and mitigation.

Monitoring of glacial lake growth can be accomplished using time series satellite images. An example is given in Figure 7, which shows satellite images taken between 1962 and 2009 of Imja lake in Nepal.

Satellite images can also be used for regular updating of the inventory database. This facilitates tracking of any changes that may occur. However, clouds can obstruct satellite image reception, particularly during the monsoon season, and information gaps may occur. Microwave remote sensing, that can penetrate cloud cover, is being employed to offset this problem. ICIMOD, with support of the European Space Agency (ESA), is continually monitoring Imja lake and its vicinity using the regular temporal RADAR dataset, i.e., Synthetic Aperture Radar (SAR) and Advanced Synthetic Aperture Radar (ASAR) data (Bajracharya et al. 2007). Use of these technologies, together with TerraSAR X data, is effective during obscured atmospheric conditions (Figures 8a, b, c).

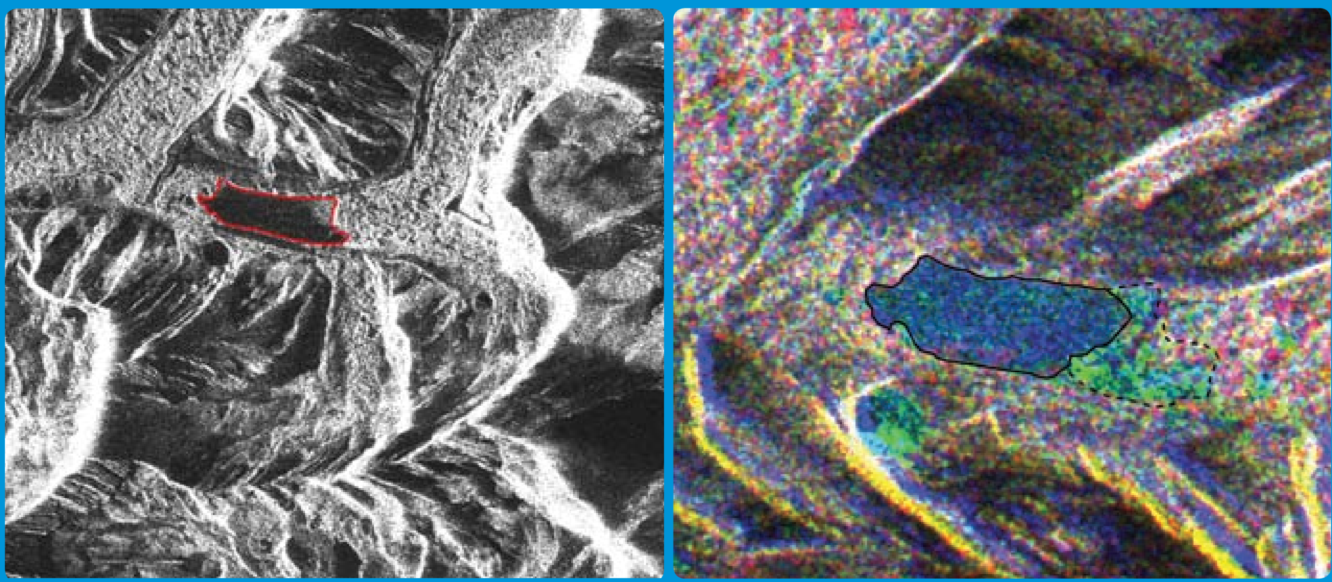
Figure 7: **Time series satellite images of different spatial resolution of Imja glacial lake and its surroundings in Sagarmatha National Park, Nepal**



a) Corona (15 Dec 1962); b) Landsat MSS (15 Oct 1975); c) Space Shuttle (02 Dec 1983); d) Landsat 5 TM (11 Dec 1989); e) Landsat 5 TM (22 Sep 1992); f) Landsat 7 ETM+ (30 Oct 2000); g) LISS 3 (19 March 2001); h) Google Earth (Feb 2003); i) Landsat 5 TM (5 Nov2005); j) ALOS AVNIR-II (11 Mar 2009).

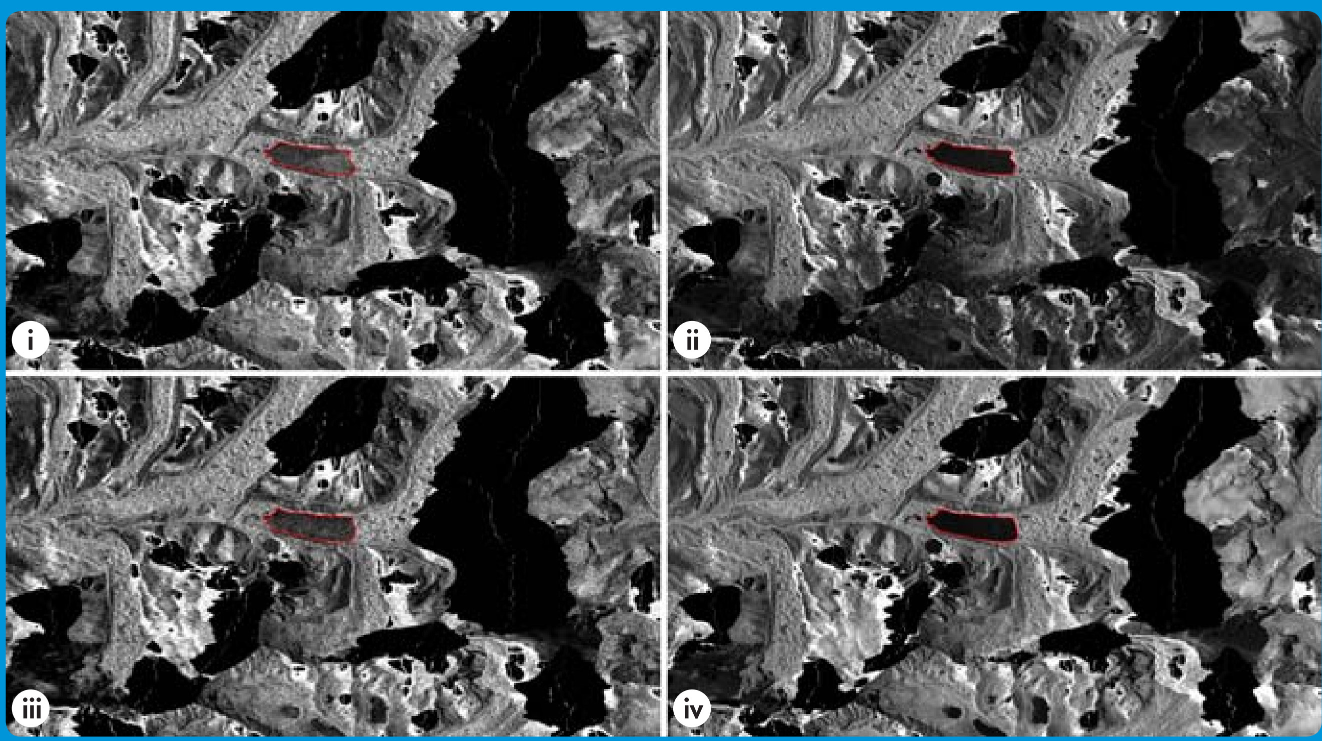
Figure 8: **Remote sensing images of Imja glacial lake in Nepal,**
a) Microwave image of ALOS PALSAR March 14, 2008; b) Colour composite image obtained by superimposing ESA ASAR RADAR images taken in 1993 (red), 1996 (green), and 2005 (blue), the unbroken polygon represents the lake area in 1993 while the dashed polygon represents the increase in area by 2005; c) Monitoring of lake through microwave remote sensing data of ESA TerraSAR and ASAR satellite images at different times i) 30 April 2009 ESA ASAR, ii) 22 October 2009 ESA ASAR, iii) 7 June 2009 Terra SAR-X , iv) 17 October 2009 Terra SAR-X

a b



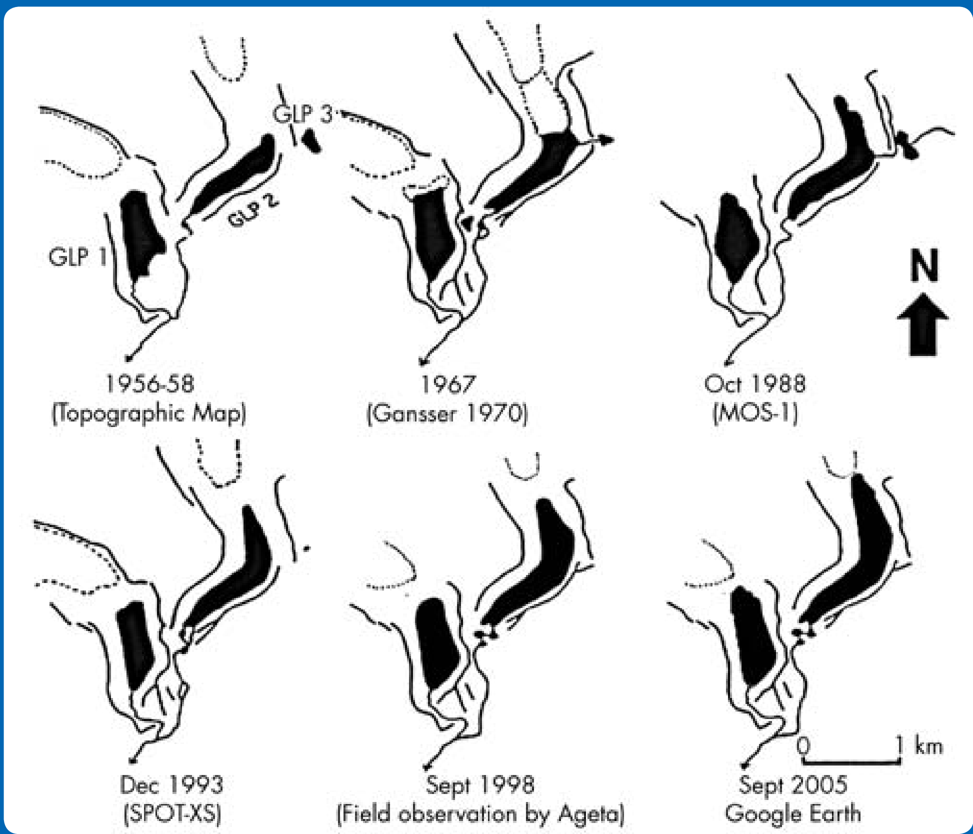
Bajracharya et al. (2007)

c



A similar approach using satellite imagery has been employed in Bhutan for the two Tarina lakes: Tarina Tso and Mouzom Tso. Figure 9 shows changes in the size and shape of the lakes in different years, as detected from a comparison of satellite images, photographs, topographic data and other information (modified from Ageta et al. 2000, in Bajracharya et al. 2007). The upper lake, Mouzom Tso, grew from 1967 to 1988 and was then blocked by a cliff in the upstream area. The lower Tarina lake expanded from 1956 to 1967. The lakes then diminished in area, possibly due to an outburst event in 1989/90 (DGM 1996), but further expansion was reported in subsequent years. Growth of both lakes continued until they reached the upstream bedrock wall, which prevented further expansion. Overtopping by a surge wave due to icefall into these lakes has been identified as an associated risk (Ageta et al. 2000; Bajracharya et al. 2007).

Figure 9: **Map showing the growth of the Tarina Tso glacial lake in Bhutan based upon topographic maps, satellite images, flight observation and other ancillary information**



modified from Ageta et al. (2000) in Bajracharya et al. (2007)

Remnant of GLOF event from Nare glacial lake, Nepal, in 1977 as seen in April 2009, Tyangboche and Mt Ama Dablam in the background

5 Regional Capacity for Studying the GLOF Risk

The four Himalayan countries that were the focus of the inventory project, Bhutan, India, Nepal and Pakistan, have a range of capacities in terms of the remote sensing applications needed for glacial lake mapping, and regular monitoring and risk assessment. They are also at different stages in terms of actual activities related to GLOF risk assessment.

Remote sensing capacity

Regional capacity

India has its own well established space programmes, viz. the National Remote Sensing Agency (NRSA), National Remote Sensing Centre (NRSC), Hyderabad; Indian Institute for Remote Sensing (IIRS), Dehradun; and the Indian Space Research Organisation (ISRO), Ahmedabad. The National Remote Sensing Centre (NRSC) at Hyderabad is one of the centres of the Indian Space Research Organisation (ISRO), under the Earth Observation Programme and Disaster Management Support Programme. NRSC is responsible for the acquisition, processing, and supply of aerial and satellite remote sensing data and continuously exploring the practical uses of remote sensing technology for multilevel (global to local) applications. It provides the necessary trained manpower through capacity building in remote sensing applications. NRSC is also providing single-window disaster management support services through the Decision Support Centre (http://www.nrsc.gov.in).

In Pakistan, the national space agency, the Space and Upper Atmosphere Research Commission (SUPARCO), established in 1961 as a Committee, was granted the status of a Commission in 1981. One of its many functions is to undertake research and conduct pilot studies based on applications of satellite remote sensing (SRS) data and geographic information system (GIS) technology to natural resources surveying, mapping, and environmental monitoring (http://www.suparco.gov.pk).

Bhutan and Nepal are not yet at such an advanced technological stage.

As yet, no specific assessment has been made of the capacity in China. But China has a well-established space programme as well as advanced capacity in remote sensing applications, GIS, and glacier research. Specifically, ICIMOD is collaborating with the Cold and Arid Regions Environmental and Engineering Research Institute (CAREERI) of the Chinese Academy of Sciences (CAS), based in Lanzhou, in the development of a new inventory of glaciers and glacial lakes for the HKH region (see Chapter 6).

UN agencies using remote sensing for disaster management

There are a number of institutions within the United Nations system that employ remote sensing for disaster management that have services relevant to the Himalayan region.

The United Nations Office for Outer Space Affairs (UNOOSA), based in Vienna, is responsible for promoting international cooperation in the peaceful use of outer space. UNOOSA also maintains a 24-hour hotline as the United Nations focal point for satellite imagery requested during disasters, and manages the United Nations Platform for Space-based Information for Disaster Management and Emergency Response (UN-SPIDER) (http://www.ossa.unvienna.org).

UNOSAT (United Nations Operational Satellite Application Programme) is the United Nations Institute for Training and Research (UNITAR) Operational Satellite Applications Programme, implemented in cooperation with the European Organization for Nuclear Research (CERN). The programme, created in 2000, provides satellite solutions to relief and development organisations and comprises UN fieldworkers, satellite imagery experts, geographers, geologists, development experts, database programmers, and Internet communication specialists. Their stated mission is "to deliver integrated satellite-based solutions for human security, peace and socio-economic development, in keeping with the mandate given to UNITAR by the UN General Assembly since 1963."

The International Charter on Space and Major Disasters is available to coordinate the use of space facilities in the event of natural and technological disasters (Rev. 3(25/4/2000).2) (http://www.disastercharter.org). This Charter can be activated during any major disaster, including GLOF events. UNOSAT can assist by providing satellite images, maps, and geographic information for relief operation and management (www.Unosat.org).

Organisations relevant for GLOF risk assessment

In the course of the inventory study, an attempt was made to identify institutions in the four countries that could undertake or were already involved in GLOF related activities. Some indication of organisations was obtained during a 'Regional Consultation Workshop on GLOF and Flash Flood Risk Assessment in the Hindu Kush-Himalayas' held from 30 July to 1 August in 2008 (ICIMOD internal report, 2008). However, it is difficult to assess the actual capabilities and activities of the various organisations and groups involved in mapping glacial lakes and assessing GLOF risk, not least because there is a continual refinement in the approaches as well as a stream of new imagery and methodologies coming on-line. The main organisations identified in the different countries, and the roles they play, are summarised below.

Bhutan

The risk of glacial lake outburst floods has been of major concern in Bhutan. The earliest known reference to dangerous glacial lakes in Bhutan relates to the scientific reconnaissance of Professor A. Gansser (1966). However, there was no documented evidence of GLOF events until the Luggye Tsho glacial lake outburst incident on 7 October 1994. This event, which caused extensive damage along the Punakha Wangdi valley, prompted investigation of glacial lakes and damage that might occur (National Report on Bhutan for World Conference on Disaster Reduction 2005). Institutions undertaking GLOF related activities in Bhutan at present include the following:

1. Department of Geology and Mines, Ministry of Economic Affairs
2. Hydro-Meteorological Services Division, Department of Energy, Ministry of Economic Affairs
3. Planning and Policy Division, Disaster Management Division, Department of Local Governance, Ministry of Home and Cultural Affairs
4. Ministry of Agriculture

The Department of Geology and Mines (DGM) of Bhutan is the government geo-scientific organisation entrusted with the responsibility for all geo-related activities in the kingdom. The Department is the leading organisation responsible for the monitoring of glaciers and glacial lakes in northern Bhutan and for mitigation of their possible outbursts. It prepared an inventory of glaciers and glacial lakes in the headwaters of major river basins in 1996 using 1:50,000 maps produced by the Survey of India that were based on air photographs of 1956 and 1958, and satellite images (DGM 1996). The DGM has carried out all the GLOF-related activities in Bhutan in cooperation with several international agencies, academic institutions in Japan and Austria, and UNDP and ICIMOD.

India

Institutions that could or are undertaking GLOF related activities in the Indian Himalayas include at least the following:

1. Wadia Institute of Himalayan Geology, Dehradun
2. GB Pant Institute of Himalayan Environment and Development, Almora
3. Birla Institute of Technology, Jaipur
4. National Institute of Disaster Management, New Delhi
5. Indian Institute of Tropical Meteorology, Pune
6. National Institute of Hydrology, Roorkee
7. Universities in India

Originally named the Institute of Himalayan Geology, the Wadia Institute of Himalayan Geology in Dehradun is an autonomous research organisation established in June 1968 under the Department of Science and Technology, Government of India. The Wadia Institute carries out basic research on Himalayan geology and related fields: geodynamic evolution, mountain building processes, geo-environment, and mineral resources. The Centre for Himalayan Glaciology at the Wadia Institute of Himalayan Geology was inaugurated on 4 July 2009. "The Glaciology Centre at the Wadia Institute of Himalayan Geology will act as a nodal centre for carrying out studies on glaciers in Uttarakhand, Jammu and Kashmir, Himachal Pradesh, and Sikkim, ... The Centre will concentrate on a broad spectrum of research in the field of glaciology. It will become an asset for the Wadia Institute of Himalayan Geology," (Tribune News Service, July 2009). The Wadia Institute collaborated as the national partner with ICIMOD on the inventory in Uttaranchal.

The GB Pant Institute of Himalayan Environment and Development (GBPIHED) is an autonomous institute of the Ministry of Environment and Forests, Government of India. GBPIHED has undertaken studies on different aspects of glacier response to climate change and its impact on Himalayan ecosystems since 1999. The Glacier Study Centre of the Institute, established in 2004, facilitates in-depth research on glacier response to climate change and its environmental and social impact in the Himalayan region. It has established field monitoring stations on several glaciers of the central and eastern Himalayas. Glacier and GLOF research has been a major activity of the Institute for over a decade.

The Birla Institute of Technology (BIT) – Jaipur Campus, India, established in 1995, is one of the leading institutions that began programmes in glaciology in concert with the Remote Sensing Division. The institute has conducted international collaborative research with the Centre for Ecology and Hydrology (CEH), Wallingford, UK, on the Gangotri glacier, and IRD (Institut de recherché pour le développement), France, on the Chhota Shigri glaciers. The Institute is in the process of preparing a glacial lake inventory in the Zanskar basin, Jammu & Kashmir. The work includes monitoring of two glacial lakes in the southern Zanskar basin formed by the recession of glaciers. Remotely sensed imagery, dating from 1989 and 2000, and GPS (global positioning system) observations from 2008, provide the basis for the survey.

The National Institute of Disaster Management (NIDM), Ministry of Home Affairs, is engaged in research and capacity building at national and international levels for managing disasters such as flash floods, drought, climate change, other extreme weather events, and their impact on agriculture, water resources, health, and related sectors.

Nepal

Nepal has gained much needed experience and expertise in GLOF-related matters from various activities in the past. Human resources from all relevant disciplines, such as geology and geomorphology, remote sensing and GIS, geotechnical engineering, hydrology, meteorology, glaciology, socioeconomics, and environment are available within government organisations and universities. Institutions that have the expertise to undertake GLOF related activities, at least in part, include the following:

1. Department of Hydrology and Meteorology
2. Water and Energy Commission Secretariat
3. Department of Water Induced Disaster Prevention
4. Central Department of Geology, Tribhuvan University
5. Central Department of Hydrometeorology, Tribhuvan University
6. Central Department of Geography, Tribhuvan University
7. Department of Environmental Science and Engineering, Kathmandu University
8. Nepal Engineering College, Centre for Disaster Studies
9. Department of Geology, Tri-Chandra Campus

The Department of Hydrology and Meteorology (DHM), Ministry of Environment, Science and Technology, is the mandated government organisation with responsibility for snow hydrology and glaciology, in addition to monitoring river hydrology, climate, agro-meteorology, sediment, air quality, water quality, limnology, and wind and solar energy. DHM has conducted a multi-disciplinary study of Thulagi and Tsho Rolpa glacial lakes in collaboration with national and international agencies,.

The Water and Energy Commission (WEC) established in 1975, was transformed into a permanent secretariat in 1981, with the objective of developing water and energy resources in an integrated and accelerated manner. It was the first government institution to investigate glacial lakes in Nepal (WECS 1987).

The Centre for Disaster Risk Studies (CDRS), Nepal Engineering College (NEC), is dedicated to applied research on disaster risk management. Some human resources are available in areas of climate change as well as flash floods, remote sensing, and GIS. The integrated study of natural disasters in Nepal embraces several planned research efforts related to floods, flash floods, climate change, and GLOFs.

The Central Department of Geology (CDG), Tribhuvan University (TU) participated in the study of the Thulagi and Tsho Rolpa glacial lakes. It employs professionals in the area of GLOFs and climate change observation.

Faculty members of the Department of Environmental Science and Engineering (DESE), Kathmandu University (KU), have been involved in the research projects on GLOF and climate change impacts on water resources; Gokyo lake water system; and solid waste and energy management in the Sagarmatha National Park. DESE has at least one professional in the area of GLOFs, glaciology, and remote sensing/GIS. The Himalayan Cryosphere, Climate and Disaster Research Centre (HiCCDRC) was established on 28 October 2009 at Kathmandu University in collaboration with the University of Colorado, Boulder, USA and is involved in the scientific investigation of glaciers and glacial lakes.

The Central Department of Geography of Tribhuvan University (TU) is also involved in research activities in the field of hazards, vulnerability, and risk assessment, including GLOFs, riverine floods, landslides, and climate change and risk reduction and adaptation strategies. There are several professionals in the area of glaciology and glacier mass balance and glacier hazards, including GLOFs.

Pakistan

ICIMOD is actively communicating with several institutions in Pakistan that are dealing with GLOF related activities, including the following:

1. Water Resources Research Institute, National Agricultural Research Centre (Islamabad)
2. Flood Forecasting Division, Pakistan Meteorological Department (Lahore)
3. Global Change Impact Studies Centre (Islamabad)
4. Focus Humanitarian Assistance (Islamabad)
5. Water and Power Development Authority (WAPDA, Lahore)

The Flood Forecasting Division has been entrusted with the responsibility of forecasting floods, flash floods, riverine floods, and all water induced disasters. In addition there are human resources in the areas of glaciology, GLOFs, climate change observation, remote sensing and GIS.

A task force on climate change and GLOFs has been formed recently to improve the exchange of information among the relevant organisations in Pakistan.

Ongoing regional programmes by ICIMOD and partners

There are many ongoing programmes in the region related to GLOFs. Some of the activities being coordinated by ICIMOD are described in the following.

Regional glacial lakes mapping and GLOF risk assessment

One of the most important regional programmes related to the theme of this study is the development of a new inventory of glacial lakes by ICIMOD in cooperation with regional partners for the entire Hindu Kush-Himalayan region. The expanded and revised inventory is being prepared to improve understanding of the characteristics of glacial lakes and the mechanism of GLOFs. The new inventory will take into account the following factors:

1. Use the same spatial reference datum (World Geographic System 1984 (WGS 84) for map projection)
2. Use the same data sources with similar data accuracy
3. Investigation for the same period as a reference year for glacial lake change analysis
4. No gaps or overlapping between different countries
5. Use the same lake classification, and one that can also be used to classify potentially dangerous lakes

In this project, efforts will be made to determine the status of glacial lakes, their changing patterns, expansion, and outburst mechanisms, and the impact on them of climate change. The capabilities of the national partner institutions will also be strengthened. Finally, inter-country cooperation will be augmented throughout the region by creation of a 'regional glacial lake information system.'

The new inventory is being prepared for the area from Afghanistan in the west to Myanmar in the east, and is being carried out by ICIMOD in conjunction with the Cold and Arid Regions Environmental and Engineering Research Institute (CAREERI) of the Chinese Academy of Sciences (CAS) and supported by Sida, the Norwegian Ministry for Foreign Affairs, and the World Bank (see Chapter 6). The revised inventory for Nepal is a part of this. The results are being compiled during 2010 and will provide an up-to-date regional inventory for the entire region.

Other ICIMOD activities

ICIMOD is also implementing a project on 'Hazard assessment and mitigation study of potential glacial lake outburst floods (GLOFs) in Nepal' in collaboration with national partner institutes, supported by the World Bank. The objectives are 1) to develop recommendations for adaptation and mitigation against GLOF hazards in Nepal; and 2) to assist Nepal in the development of an overall strategy to address the risk from GLOFs in the future. The project aims to assess hazards from critical (potentially dangerous) lakes in Nepal and to investigate vulnerable downstream areas. The intent is also to strengthen partnerships among key stakeholders for development of a risk reduction strategy. Three lakes were selected as project sites: Imja, Thulagi, and Tsho Rolpa. ICIMOD is collaborating with DHM; WECS; Central Department of Hydrology and Meteorology/Tribhuvan University (CDHM/TU); Ministry of Water Resources, Government of Nepal (MoWR); Department of Mines and Geology, Government of Nepal (DMG); Central Department of Geology/Tribhuvan University (CDG/TU); Geographic Information System and Integrated Development Centre (GISIDC); Kathmandu University (KU); Nepal Electricity Authority; private hydropower companies; and various NGOs. International institutions such as WWF-Nepal, WB, UNDP, and Department for International Development, UK (DFID) are also sharing resources and knowledge.

Since 2008, ICIMOD has implemented a three-year project funded by Sida on 'Too much water, too little water - Local adaptation strategies to climate induced water stress and hazards in the greater Himalayan region'. One aim is to strengthen capacity within ICIMOD and among national partners for undertaking regular monitoring of glaciers, snow and ice fields, and pro-glacial lakes. This will help provide decision makers in the region (and beyond) with timely and adequate data and information on the status of these features.

ICIMOD, together with the Centre for International Climate and Environmental Research, Oslo (CICERO), and UNEP-GRID Arendal, has been undertaking a feasibility study for a 'Himalayan climate change impact and adaptation assessment' (HICIA) with a focus on GLOF and flash flood risk assessment, as well as assessment of other impacts.

A regional project entitled 'Flash flood risk reduction – Strengthening capacity in the Hindu Kush-Himalaya' is also being undertaken by ICIMOD working with regional partners with funding from the United States Agency for International Development, Office for Foreign Disaster Assistance (USAID/OFDA). During the previous two phases of the project, emphasis was placed on a baseline assessment of flash flood risk management in the region, strengthening the capacity of key stakeholders, and awareness raising. The main objective of the present phase (2010-2012) is to contribute to reducing the vulnerability of mountain communities to flash floods in the region through capacity building of key stakeholders. Glacial lake outburst floods are causative factors in propagating flash floods downstream, thus this type of project is also contributing to GLOF-related risk reduction. Geographically, the project will focus on China, India, Nepal, and Pakistan.

Since 2001, ICIMOD has collaborated with the regional partner countries Bangladesh, Bhutan, China, India, Nepal, and Pakistan on a long-term project 'Regional cooperation in flood forecasting and information exchange in the HKH region' supported by funding from the United States Agency for International Development, Office for Foreign Disaster Assistance (USAID/OFDA). Linked to this, application of satellite rainfall estimation (SRE) in the Hindu Kush-Himalayan region is a regional project implemented by ICIMOD and its partner countries. The aim of the project is to strengthen regional cooperation in data and information exchange and to build the capacity of partner institutions in satellite rainfall estimation and its use with the end goal of minimising the loss of lives and property by reducing natural vulnerability in the HKH region, in particular in the Indus, Ganges, and Brahmaputra basins (Shrestha et al. 2008). Although, the project is not directly a GLOF project, it has a causative relationship with GLOF phenomena.

ICIMOD and the Ministry of Foreign Affairs, Government of Finland, signed an agreement in December 2009 for a three-year collaborative project to establish a regional flood information system. The project will be implemented by ICIMOD in close collaboration with the World Meteorological Organization (WMO) and the six ICIMOD regional partner countries. The long-term goal is to minimise loss of lives and livelihoods by providing timely warning of floods and thus reducing flood vulnerability in the Hindu Kush-Himalayan region, in particular in the Ganges-Brahmaputra-Meghna and Indus river basins. The regional flood information system developed under this project will help improve flood forecasting and disaster preparedness, improve regional cooperation in flood risk reduction, strengthen upstream-downstream linkages, and contribute to reducing loss of lives and livelihoods.

6 Establishment of an Inter-country Regional GLOF Risk Monitoring Network

Many types of glacial lake have formed in the past in various parts of the world. In regions where mountain farming populations have lived for centuries and where accumulation of documentary records was customary, a long history of the dangers associated with the occasional outburst of such lakes has been preserved. Thus there are at least sporadic records of catastrophic events emanating from regions such as the European Alps, Scandinavia, and Iceland, going back several centuries. Most of these lakes, however, had formed as a result of advancing glaciers that blocked tributary, ice-free valleys. They are best classified as 'ice-dammed lakes'. They are quite distinct from the glacial lakes being considered here, but the accumulated knowledge of their development and periodic drainage is quite well known and relevant. More recently (late 19th and 20th centuries) glacial lake outburst floods have been documented in Alaska, British Columbia, and the Andes. Investigation of many of these occurrences has added to the volume of knowledge concerning this destructive phenomenon.

As the science of glaciology developed after about 1880, such ice-dammed lakes became objects of academic study (e.g., Ahlmann 1948; Thorarinsson 1939, 1940, 1943; Björnsson 2009). Iceland has experienced a special form of glacial lake outburst resulting from volcanic activity beneath several of that country's ice caps, especially Vatnajökull (Thorarinsson 1953; Björnsson 1974). Some of these 'jökulhlaups' have produced immense volumes of water estimated to exceed the flow of the River Amazon in full flood.

With the onset of climate warming about 1850-1905 (generally considered as the end of the Little Ice Age), glaciers in many parts of the world began to thin and their termini to retreat. Thus another form of meltwater lake became increasingly common – the frontal, supra-glacier, and/or moraine-dammed lake. The continued trend in climate warming, despite certain reversals (1960s and 1970s), has resulted in the formation of an increasing number of moraine-dammed lakes. This pattern either was not noticed or did not occur to any significant extent in the Himalayas until well into the second half of the 20th century. Although Kenneth Hewitt long ago recorded the occurrence of glacial lake outburst floods in northern Pakistan, these were ice-dammed lakes (Hewitt1982).

By the 1970s, there had been a number of outbursts from the supra-glacial/ moraine-dammed type of lake in the central and eastern Himalayas. They caused appreciable damage to people and property living in downstream lower lying areas. Despite this, there was no concerted government response. For Nepal, at least, 1985 proved a critical turning point, although even then wide appreciation of the significance of climate warming and the debate over its cause did not arise.

The 4 August 1985, catastrophic drainage of the moraine-dammed lake (Dig Tsho) that had formed behind the end moraines of the retreating and thinning Langmoche glacier in the eastern section of Sagarmatha (Mt Everest) National Park proved a pivotal event. Eleven kilometres downstream of Dig Tsho, an Austrian Aid hydro-electric facility (Namche Small Hydel Project) that was nearing completion was totally destroyed within minutes of the outburst. Over a distance of 60 kilometres, fourteen bridges, more than two dozen homes, and much agricultural land, were destroyed or damaged. That only four or five lives were lost was in part because the outburst flood coincided with traditional/religious celebrations so that few of the local people were near the affected river. The timing of the catastrophe also coincided with the summer monsoon hiatus in the trekking season (much of the Dudh Kosi drainage below the confluence of the Bhote Kosi and Imja Khola rivers carries long sections of the popular trekking route to the Mt Everest base camp – it would be instructive to complete a retrospective worst case assessment of potential loss based on the assumption that the outburst occurred at the height of the trekking season).

Nevertheless, serious local losses occurred for many months after the actual event due to continuing instability of sections of the valley slopes affected by passage of the flood/debris flow.

Coincidental with the Dig Tsho outburst flood, a United Nations University mountain hazards mapping project in the Khumbu (Ives and Messerli, project coordinators) was nearing completion. This project was operating in association with ICIMOD and included the field training of several young Nepali scholars (Ives and Messerli 1981). It ensured that a first-hand examination of the impacts of the outburst flood could be undertaken by two of the Swiss graduate student team members (Vuichard and Zimmermann). Much assistance was also provided by Dr Victor Galay, who at that time was serving as a consultant to WECS, Government of Nepal.

The extent of the damage and the overall shock of the Dig Tsho outburst prompted Dr Colin Rosser, then Director General of ICIMOD, to invite Ives to undertake an assessment of the event and to prepare a report for publication (Ives 1986). This was supplemented by scientific papers prepared by Vuichard and Zimmermann (1986, 1987).

Ives's report made a number of pertinent recommendations:

1. To identify and map other potentially dangerous lakes in the Khumbu
2. To apply currently available remote sensing technology to search for such lakes over a wider area as a response to the extreme difficulty of terrain access
3. To attempt the mapping of areas downstream of such lakes that would potentially be at risk as a basis for possible control on future land use
4. To undertake detailed field surveys of lakes that were thought to be especially dangerous
5. To develop an archive of replicated photographs as a means of providing a visual record of glacial lake development; it was recommended that permanent photo stations be incorporated into this process

An exploratory inspection of available air photographs and ERTS (Earth Resources Technology Satellite)/LANDSAT imagery led to the identification of an expanding supra-glacial lake on the surface of the Imja glacier a few kilometres south of Mt Everest. By chance, Ives had acquired photographs from the collection of his then deceased colleague, Professor Fritz Müller, who had taken several hundred photographs of the glaciers and glacial landforms during his participation in the 1956 Swiss Everest/Lhotse expedition. Several of them demonstrated that in 1956 no lake existed on the lower tongue of the Imja glacier, only several small melt ponds. In contrast, by 1985 it could be shown that a large lake had formed in the intervening period with a surface area of about 0.6 sq.km. This led to the first efforts to plot the development of what has since become known as Imja Tsho (or Imja lake), today identified as potentially one of the more dangerous lakes in the Himalayas (Figure 10).

In this manner, ICIMOD, in collaboration with WECS, became a lead institution in the Himalayan region to identify with the problem of glacial lake outburst floods. Due to lack of government interest and shortage of funds, there followed a period of reduced activity. Nevertheless, strong university interest persisted. Thus, graduate students who were working with Ives, and in particular, Ms June Hammond (1988), University of Colorado, USA; Dr Teiji Watanabe, now with Hokkaido University, Japan (Watanabe et al. 1994); and Dr Alton Byers, now senior scientist with The Mountain Institute, West Virginia, USA (Byers 2007), continued independent research on the progressive development of Imja Tsho. Much additional research has also been undertaken by Nagoya University, Japan (Fujita et al. 2009).

Revival of interest occurred with the realisation that the glacial lake Tsho Rolpa, situated in the watershed to the west of the Khumbu (Rolwaling Himal), was expanding rapidly and the lake level had risen so that it was draining across the lowest point on the glacier's end moraine. This led to a great amount of activity that had an effect on the economy of the lower valley. For example, some hundreds of people were temporarily evacuated. Because no lake outburst occurred, an attitude of disbelief and disinclination to take the situation seriously is reported to have emerged. Eventually, with foreign aid (Government of the Netherlands), a reinforced channel was constructed through the moraine dam, the lake level was lowered by three metres, and a small hydroelectric station and an early warning system were installed (see Chapter 4). Tsho Rolpa has remained semi-stable until this day; it is now classified as one of the potentially dangerous glacial lakes in the Nepal Himalaya.

Figure 10: **Repeat Photography of Imja glacier and lake, Nepal, at an interval of 50 years**

Imja glacier 1956 (Photo: Fritz Müller, archives of Alton Byers, The Mountain Institute, courtesy Jack Ives)

Imja glacier 2007 (Alton Byers, The Mountain Institute)

In addition, Dr T. Yamada and several of his Japanese colleagues undertook extensive field and airborne investigations in association with WECS (Yamada 1998a).

It is only during the last decade or so that there has been an understanding, at least at a generalised level, that there is probably a causal connection between contemporary climate warming and the creation of new glacial lakes and their sometimes very rapid expansion. During this period, ICIMOD has undertaken a series of investigations, deploying both field teams and employing increasingly sophisticated remote sensing. This work, discussed in the previous chapters, has produced extensive glacier and glacial lake inventories, originally for the the Nepal and Bhutan Himalaya (Mool et al. 2001a and 2001b), and subsequently, in collaboration with institutional partners, preliminary regional reports for most sections of the Hindu Kush-Himalayas. Concomitantly, a significant cadre of staff members has received training in the application of remote sensing techniques, together with a growing amount of fieldwork experience.

During the same period, the issue of potential catastrophe from the sudden outburst of glacial lakes has begun to receive extensive attention by the news media. Unfortunately, much of this news release has led to excessive claims of a doomsday nature, coupled with other melodramatic accounts of the deleterious impacts of climate warming on the Himalayan glaciers at large. Ives (2004, 2005) has published criticisms of several of these gross exaggerations. These exorbitant claims create a potential for significant damage – social, economic, and especially political. It therefore becomes even more urgent that a firm scientific base be created so that rational response policies can be put in place. Such responses need to be: prevention, in terms of reducing the potential for catastrophic glacial lake drainage (engineering interventions); installation of early warning systems; and collaboration with local people to ensure the best possible responses to early warning and mitigation activities and to adaptation. However, while steps can be taken immediately to approach these various objectives, it is vital that a much fuller scientific base be established so that the relationships between climate warming and glacier response be more completely understood. Consideration should be given to broadening the GLOF risk assessment approach to include analysis of the hydrological implications of climate warming as they relate to snow and glaciers and the supply of water downstream (Alford et al. 2009; Armstrong et al. 2009). Similarly, continual refinement in remote sensing techniques and their application are needed. All of these aims will require accelerated training of highly qualified applied scientists and technicians; enlargement of a long-term data base in hydrology, meteorology, and glaciology; specialised engineering; incorporation of local communities into the assessment and response systems; and development of partnerships amongst the many engaged institutions and universities across the region.

ICIMOD is uniquely placed to meet these demanding targets; to act in the forefront of research and its application; to assist with the training of a cadre of young professionals; and to perform its primary function as a lead partner and go-between amongst the several highly competent institutions and universities of the region, many of whom are already actively involved within their own sectors of the Hindu Kush-Himalayas. Finally, cooperation with the many scientists from beyond the region, who have had experience in relevant research, needs to be encouraged.

It is essential to utilise the most up-to-date methods to identify and to monitor continued development of glacial lakes and their short-term changes across the Hindu Kush-Himalayan region. This implies

1. assessment of latest developments in relevant remote sensing technology and imagery analysis;
2. review of work on glacial lakes completed to date;
3. update the inventory of institutions and individual experts within the region undertaking related studies;
4. recognise the heavy dependence on remote sensing applications because of the vast area involved and the great difficulties of ground access;
5. consideration of what attempts should be made to counter, through the news media and relevant government and international institutions, the dangers of over-dramatisation in current reporting on the assumed imminence of glacial lake outburst floods and their impacts; and
6. archive the latest scientific information to provide a base for national policy makers dealing with GLOF risk management and to share knowledge with the global scientific community.

Point (4) subsumes the critical importance of determining the advantages and limitations of remote sensing applications. It follows that an attempt is needed to produce a ranking of potentially unstable glacial lakes. It is now well established (Hambrey et al. 2008; Fujita et al. 2009; Watanabe et al. 2009) that the rate of glacial lake enlargement alone cannot be regarded as a reliable measure of instability. Thus the ranking proposed above should become a tool for determining the need for detailed field survey. Sufficient is now known about the factors that have a bearing on glacial lake stability that a check list of specific objectives for investigation in the field can be readily prepared:

1. Changing lake level and rate of change
2. Changing lake depth – results both from change in surface level due to increased inflow of meltwater (increase in level) or accelerated outflow due to cutting down of the lake threshold (lowering); melting of sub-lacustrine ice
3. Condition of dam (including soil mechanics, internal temperature – existence of permafrost, buried ice, and determination of rate of melting)
4. Determination of the lake water balance
5. Proximity of possible destabilising 'triggers' for inducing lake discharge, e.g., steep rock walls as sources of rock fall and ice and snow avalanches, condition of glacier terminus and estimated likelihood for collapse of glacier ice into lake; any large scale activity in these categories could cause a surge wave in a glacial lake that may have sufficient force to overcome a moraine dam (e.g., Dig Tsho, 1985)
6. Assessment of the potential danger of glacial lake outburst as induced by earthquake tremor is most likely beyond current competence

The feasibility of establishing an inter-country regional GLOF risk monitoring network is very high. The preceding sections of this report indicate that such a system is beginning to take shape. Bilateral collaboration, even trilateral, is already well advanced. Rapidly growing awareness of the seriousness of the widespread risk of catastrophic glacial lake outburst and the enormous attention that it is attracting from the various levels of the news media will surely accelerate this process.

Preliminary recommendations for future needs in relation to institutional partnerships and capacities for GLOF risk monitoring

ICIMOD is an international organisation with a regional mandate to partner organisations both within and outside government, including, non-government organisations (NGOs) and civil society, the private sector, and other international organisations. It can use its mandate to further cooperative developments across the region in terms of glacial lake mapping and GLOF risk assessment.

ICIMOD has already established significant partnerships with the national institutions of the regional member countries and has also established relationships with the international agencies such as ESA, GLIMS, GlobGlacier, NOAA (National Oceanic Atmospheric Agency), USGS (United States Geological Survey), National Snow and Ice Data Center, University of Colorado, USA, and Keio University. It is noteworthy here that ICIMOD has contributed to the GLIMS global initiative to monitor the world's glaciers by inserting the database of glaciers of Nepal generated in 2001 in the GLIMS database in 2008. ICIMOD has been designated as the regional coordinator of GLIMS.

The following two fundamental priorities have been identified during the 'Regional Consultative Workshop on Remote Sensing of the Cryosphere – Assessment and Monitoring of Snow and Ice in the HKH Region held from 31 May to 2 April in 2009' (ICIMOD 2009a, internal report):

1. To strengthen snow and ice cover mapping and the monitoring and mapping of the regional distribution of glaciers and glacial lakes
2. To establish links with global initiatives NSIDC (National Snow and Ice Data Centre)/GLIMS and WGMS) as well as local cooperation at sub-regional levels.

The inter-country network should ensure that appropriate data collection using satellite imagery is undertaken in a coordinated manner across the region, and the data collected used to develop a regularly updated map of glaciers and glacial lakes. This should be used for identification of risks, detailed studies outlining any mitigation measures that are necessary, and monitoring of changes.

Thulagi glacial lake, Nepal, IKONOS-2 image
from 14 November 2009 overlaid on Google Earth DEM

7 Conclusions and Recommendations

During the preparation of this report, an effort was made to accumulate information that would contribute to an understanding of potentially dangerous glacial lakes and how they are forming. This was extended to develop an approach for determining the degree of vulnerability to lake outburst across the Hindu Kush-Himalayan region, with emphasis on Bhutan, India, Nepal, and Pakistan. The most pertinent conclusions and recommendations are listed below.

The application of remote sensing is the most effective first phase approach in GLOF risk reduction and preparedness. It facilitates rapid and complete coverage of large and extremely remote mountainous areas, thus allowing potentially dangerous localities to be pin-pointed for closer inspection. This is important because the total area of such localities will be a small percentage of the entire region under initial survey. In this manner, time and expenses are conserved. Nevertheless, reliance on in-situ field inspection is unlikely to be replaced, at least in those cases where individual lake stability needs to be assessed.

Compilation of a standardised glacial lake inventory of the entire HKH region is essential in view of the realisation that the potential for serious losses to glacial lake outburst appears to be growing steadily. Such an inventory must be up-dated periodically. This has become highly practical in recent years with progressively inexpensive access to remotely sensed imagery and more sophisticated methods for its analysis.

Potentially dangerous glacial lakes must be provisionally identified and prioritised for further investigation. Methods to be used for prioritisation have been detailed in the body of this report. Potentially dangerous lakes must be monitored on a continuing basis. High resolution time series satellite images will provide the means of achieving this economically. Continued assessment of the glaciers, end and lateral moraines, lake limits, and outflow characteristics, together with the terrain surrounding the prioritised lakes, will be necessary.

It is emphasised that ranking of glacial lakes that are assumed to present a high degree of instability is problematic. Thus, a list of the largest and most rapidly expanding lakes that are also situated above areas of intensive human utilisation is necessarily a first step. A more complete assessment and eventual ranking will require intensive fieldwork, including the application of sophisticated geophysical techniques. It will also require establishment of the vulnerability of human assets in the downstream area.

Over-flight observations of the prioritised lakes and their immediate downstream areas should be maintained on a regular basis. Detailed field investigation of a selection of glacial lakes, especially in Nepal and Bhutan, and upstream sections in neighbouring China where lake outbursts have the potential for crossing international borders, need special attention. Comparable work, in partnership with the relevant agencies in India, should involve similar efforts, for example, in the Sutlej basin of Himachal Pradesh. Above all there is an urgent need for region-wide collaboration in the development of standardised approaches and, eventually, of uniform policies aimed at early warning and hazard mitigation.

South-South collaboration should be encouraged for sharing know-how and experiences for GLOF risk management. As an example, consideration should be given to invite to the Himalayas Andean professionals who have successfully tackled problems of GLOF risk mitigation in the Peruvian Andes.

Continuation of the mapping of terrain characteristics downstream of potentially dangerous lakes should be maintained. Greater efforts are required to ensure close rapport with local people. More attention must be given to the question of achieving active collaboration, for example, so that inadvertent or mischievous damage to any early warning system that may be installed is avoided.

Consideration should be given for the employment of a reliable local person or persons, to make two inspections each year of the condition of the prioritised lakes in their vicinity. Special attention should be paid to lake outlets and levels. For example in the case of Nepal, local Sherpas from Dingboche, or another village close to Imja Lake, should be recruited and asked to file a report following each inspection. (As an example, Icelandic farmers were encouraged (voluntarily) in the 1930s to monitor that country's numerous glaciers. This led to creation of an excellent national glacier inventory that continues to be up-dated annually to this day.)

The availability of current information and communication technology (ICT) suitable for rural application of early warning systems should be evaluated. This will enhance possibilities for installation of the most up-to-date systems to ensure near-instant warning of danger to a large population. There are examples of comparatively simple and highly effective CDMA (Code Division Multiple Access) and SMS (Short Message Service) communication systems in place for early warning against tsunami; the applicability of these should be assessed.

It is recommended that a complete bibliography on glacial lake research world-wide should be developed. This could then form the data base for compilation of a specific repository of all available publications and internal reports within the ICIMOD library system. This would provide an invaluable asset for country partner institutions that are collaborating with ICIMOD.

There is a significant number of publications arising from a series of investigations to determine the degree of danger from the potential break of the landslide dam holding up Lake Sarez in the Tajikistan High Pamir. While this is not a glacial lake (it was dammed following an earthquake-induced massive landslide in 1911) the related field experience, and problems with over-dramatised news media reporting render it highly relevant to the issue at hand (e.g., ISDR, United Nations 2000; Science, 18th December 2009: Richard Stone).

It would be highly valuable to work with government authorities for the development of national policy guidelines to deal with the problem of potential glacial lake outbursts and GLOF risk management. This should include the establishment of principles for risk assessment. Regional collaboration among or between the governments in the events of transboundary disaster, such as GLOF risk assessment and mitigation, is essential. There is a need to accelerate inter-governmental collaborative researches on glacial hazards and GLOF risk management as well as development of a mechanism of inter-governmental collaboration for sharing data and information. A regional convention of inter-governmental expert groups should identify and make recommendations on details of collaboration and the role of national governments, and draw action plans for GLOF risk management.

References

Ageta, Y; Iwata, S (1999) *The assessment of glacier lake outburst flood (GLOF) in Bhutan,* Report of Japan-Bhutan joint research 1998. Nagoya: Nagoya University, Institute for Hydrospheric-Atmospheric Sciences

Ageta, Y; Iwata, S; Yabuki, H; Naito, N; Sakai, A; Narama, C; Karma, T (2000) 'Expansion of glacier lakes in recent decades in the Bhutan Himalayas.' In *Debris-covered glaciers*, Proceedings of a workshop held in Seattle, Washington, USA, September 2000, pp. 165-175. Wallingford: International Association of Hydrological Sciences

Ageta, Y; Naito, M; Nakawo, M; Fujita, K; Shankar, K; Pokhrel, AP; Wangda, D (2001) 'Study project on the recent rapid shrinkage of summer-accumulation type glaciers in the Himalayas, 1997-1999.' *Bulletin of Glaciological Research* 18: 45-49

Ahlmann, HW (1948) *Glaciological research on the North Atlantic Coasts*, Research series No 1. London: Royal Geographical Society

Alford, D; Armstrong, R; Racoviteanu, A (2009) *Glacier retreat in the Nepal Himalaya: The role of glaciers in the hydrologic regime of the Nepal Himalaya,* report prepared for the World Bank, South Asia Sustainable Development (SASDN), Environment and Water Resources Unit

Armstrong, R; Alford, D; Racoviteanu, A (2009) 'Glaciers as indicators of climate change: The special case of the high elevation glaciers of the Nepal Himalaya.' *Sustainable Mountain Development* (ICIMOD), Water storage 56: 4-16

Bajracharya, SR (2009) *Glacial lake outburst floods risk reduction activities in Nepal.* Paper presented at Asia Pacific symposium on New Technologies for Prediction and Mitigation of Sediment Disasters, 18-19 November 2009, Tokyo, Japan

Bajracharya, SR; Gurung, DR; Uddin, K; Mool, K; Shrestha, BR (2009) *Mapping and inventory of glaciers using remote sensing data and techniques: Hands on training manual.* Unpublished internal document, ICIMOD, Kathmandu

Bajracharya, SR; Mool, PK; Shrestha, BR (2007) *Impact of climate change on Himalayan glaciers and glacial lakes: Case studies on GLOF and associated hazards in Nepal and Bhutan.* Kathmandu: ICIMOD

Bajracharya, SR; Mool, PK; Shrestha, BR (2008) 'Global climate change and melting of Himalayan glaciers.' In Ranade, PS (ed) *Melting glaciers and rising sea levels: Impacts and implications*, pp.28-46. Hyderabad: Icfai University Press

Bhagat, RM; Kalia, V; Sood, C; Mool, PK; Bajracharya, S (2004) *Inventory of glaciers and glacial lakes and the identification of potential glacial lake outburst floods (GLOFs) affected by global warming in the mountains of the Himalayan region: Himachal Pradesh Himalaya, India.* Unpublished project report, with database on CD-ROM, prepared for APN and ICIMOD, Kathmandu, by Himachal Pradesh Agricultural University, Palampur, India

Björnsson, H (1974) *Explanation of jökulhlaup from Grimsvötn, Iceland. Jökull* 24: 1-26

Björnsson, H (2009) 'Jökulhlaup in Iceland: Sources, release and drainage.' In Burr, DM; Carling, PA; Baker, VR (eds) *Megaflooding on Earth and Mars*, pp 50-64. Cambridge: Cambridge University Press

Bolch, T; Buchroithner, MF; Peters, J; Baessler, M; Bajracharya, S (2008) 'Identification of glacier motion and potentially dangerous glacial lakes in the Mt. Everest region, Nepal using spaceborne imagery.' *Natural Hazards Earth System Sciences* 8: 1329-1340

Byers, AC (2007) 'An assessment of contemporary glacier fluctuations in Nepal's Khumbu Himal using repeat photography.' *Himalayan Journal of Science* 4: 21-26

Carson, B (1985) *Erosion and sedimentation processes in the Nepalese Himalaya*, Occasional paper No. 1. Kathmandu: ICIMOD

GoB (2005) *National report on Bhutan for world conference on disaster reduction, 18-22 January 2005, Kobe, Japan*. Thimpu: Government of Bhutan, Ministry of Home Affairs, Department of Local Governance

GoB (1996) *Glaciers and glaciers lakes in the headwaters of major river basins of Bhutan*. Thimpu: Government of Bhutan, Ministry of Trade and Industry, Division of Geology and Mines

Fujita, K; Sakai, A; Nuimura, T; Yamaguchi, S; Sharma, RR (2009) 'Recent changes in Imja glacial lake and its damming moraine n the Nepal Himalaya revealed by in situ surveys and multi-temporal ASTER imagery.' *Environmental Research Letter* 4: 045205

Gansser, A (1966) 'Geological research in the Bhutan Himalaya.' In *The Mountain World, 64/65*, pp 88-97. Zurich: The Swiss Foundation for Alpine Research

Gergan, JT; Thayyen, RJ; Morup, T (2009) *Phutse glacial lake outburst flood, Ladakh range, Leh, Ladakh, Jammu and Kashmir*. Second India Disaster Management Congress, 4-6 November 2009, pp 75-76. New Delhi: National Institute of Disaster Management

Hambrey, MJ; Quincey, DJ; Glasser, NF; Reynolds, JM; Richardson, SJ; Clemmens, S (2008) 'Sedimentological, geomorphological and dynamic context of debris-mantled glaciers, Mount Everest (Sagarmatha) region, Nepal.' *Quaternary Science Reviews* 27: 2361-2389

Hammond, JE (1988) *Glacial lakes in the Khumbu region, Nepal: An assessment of the hazards*. MSc thesis, University of Colorado, Department of Geography, Boulder

Hanisch, J; Delisle, G; Pokhrel, AP; Dixit, AP; Reynolds, JM; Grabs, WE (1998) 'The Thulagi glacier lake, Manaslu Himal, Nepal: Hazard assessment of a potential outburst.' In Moore, D; Hunger, O (eds) *Proceedings of the 8th International Congress, International Association for Engineering Geology and Environment*, 21–25 September 1998, Vancouver, Canada, pp. 2209-2215. Vancouver: Tire-A-Art Offprint

Häusler, H; Leber, D (1998) *Final report of Raphstreng Tsho Outburst Flood Mitigatory Project (Lunana, Northwestern Bhutan)* Phase I. Vienna: University of Vienna, Institute of Geology

Häusler, H; Leber, D; Schreilechner, M; Morawetz, R; Lentz, H; Skuk, St; Meyer, M; Janda, Ch; Burgschwaiger, E (2000) *Final report of Raphstreng Tsho Outburst Flood Mitigatory Project (Lunana, Northwestern Bhutan)* Phase II. Vienna: University of Vienna, Institute of Geology

Hewitt, K (1982) 'Natural dams and outburst floods of the Karakoram Himalaya.' In Glen, JW (ed) *Hydrological aspects of Alpine and high mountain areas,* IAHS publication No 138, pp 259-269. Wallingford: International Association of Hydrological Sciences

Hewitt, K (2009) *Glaciers get a surge of attention in the Karakoram Himalaya*. American Geophysical Union website. www.agu.org/sci_soc/eishewitt.html. (accessed 10 March 2010)

Horstmann, B (2004) *Glacial lake outburst floods in Nepal and Switzerland – New threats due to climate change*. Bonn: Germanwatch. www.germanwatch.org (accessed 15 May 2010)

Huggel, C; Haeberli, W; Kääb, A; Hoelzle, M; Ayros, E; Portocarrero, C (2003) 'Assessment of glacier hazards and glacier runoff for different climate scenarios based on remote sensing data: A case study for a hydropower plant in the Peruvian Andes.' In *Observing our Cryosphere from Space, Proceedings of EARSeL-LISSIG workshop held* 11-13 March 2002, Berne, Switzerland, pp 22-33. Paris: EARSel. www.eproceedings.org/static/vol02_1/contents.html (accessed May 2009)

Huggel, C; Kääb, A; Haeberli, W; Teysseire, P; Paul, F (2002) 'Remote sensing based assessment of hazards from glacier lake outbursts: A case study in the Swiss Alps.' *Canadian Geotechnical Journal* 39:316–330

ICIMOD (2008) *Internal report on regional consultation workshop on GLOF and Flash Flood Risk Assessment in the Hindu Kush-Himalaya*, 30 July-1 August 2008, Kathmandu, Nepal. Unpublished internal report, ICIMOD, Kathmandu

ICIMOD (2009a) *Internal report on regional consultative workshop on Remote Sensing of the Cryosphere - Assessment and Monitoring of Snow and Ice in the Hindu Kush Himalaya Region, 31 March-2 April 2009, Kathmandu, Nepal*. Unpublished internal report, ICIMOD, Kathmandu

ICIMOD (2009b) *Progress report for the Project 'Hazard Assessment and Mitigation Study of Potential GLOF lakes in Nepal.* Unpublished internal report, ICIMOD, Kathmandu

ISDR (2000) *Usoi landslide dam and Lake Sarez: An assessment of hazard and risk in the Pamir Mountains, Tajikistan*, ISDR Prevention Series, No1. Geneva: United Nations, International Strategy for Disaster Reduction

Ives, JD (1986) *Glacial lake outburst floods and risk engineering in the Himalaya: A review of the Langmoche disaster, Khumbu Himal, 4 August1985*, Occasional paper No 5. Kathmandu: ICIMOD

Ives, JD (2004) 'What are the facts? Misleading perceptions, misconceptions, and distortions.' In Ives, JD *Himalayan perceptions: Environmental change and the well-being of mountain peoples,* pp211-228. London: Routledge

Ives, JD (2005) 'Global warming: A threat to Mount Everest?' *Mountain Research and Development* 25 (4): 394-398

Ives, JD; Messerli, B (1981) 'Mountain hazards mapping in Nepal: Introduction to an applied mountain research project.' *Mountain Research and Development* 1: 223-230

Kääb, A; Huggel, C; Fischer, L; Guex, S; Paul, F; Roer, I; Salzmann, N; Schlaefli, S; Schmutz, K; Schneider, D; Strozzi, T; Weidmann, Y (2005) 'Remote sensing of glacier- and permafrost-related hazards in high mountains: an overview.' *Natural Hazards and Earth System Sciences 5*: 527-554

Karma, T; Ageta, Y; Naito, N; Iwata, S; Yabuki, H (2003) 'Glacier distribution in the Himalayas and glacier shrinkage from 1963 to 1993 in the Bhutan Himalayas.' *Bulletin of Glaciological Research* 20: 29-40

Karma, T; Ghalley, KS; Thinley, U (2008) *Hazard zonation for glacier lake outburst flood along Punatshang chu from Khuruthang to Lhamoyzinkha. (eds. Y. Dorji),* DGM – NCAP Project (Oct. 2006 – May 2008)

Khanal, NR; Koirala, H; Nepal, P; Rai, D; Khanal, B; Sigdel, S; Sharma, AR (2009) *GLOF risk assessment of the Imja, Tsho Rolpa and Thulagi glacial lakes in Nepal*. Unpublished report for ICIMOD, Kathmandu, Nepal

LIGG; WECS; NEA (1988) *Report on first expedition to glacier and glaciers lakes in the Pumqu (Arun) and Poiqu (Bhote-Sun Kosi) river basin, Xizang (Tibet), China: Sino-Nepalese investigation of glacial lake outburst floods in the Himalaya*. Beijing: Science Press

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

McKillop, RJ; Clague, JJ (2007) 'Statistical, remote sensing-based approach for estimating the probability of catastrophic drainage from moraine-dammed lakes in southwestern British Columbia.' *Global and Planetary Change* 56: 153-171

Modder, S; van Olden, Q; (1996) *Engineering-geomorphological analysis of moraine dam in the Nepal Himalayas, A detailed survey (scale 1:1500) at Tsho Rolpa glacier lake, Rolwaling valley, Dolakha District, East Nepal*. MSc thesis, Vrije Universiteit Amsterdam, Faculty of Earth Sciences, Amsterdam

Mool, PK (1995) 'Glacier lake outburst floods in Nepal.' *Journal of Nepal Geological Society* 11: 273-280

Mool, PK; Bajracharya, SR; Joshi, SP (2001a) *Inventory of glaciers, glacial lakes, and glacial lake outburst floods: Monitoring and early warning systems in the Hindu Kush-Himalayan regions - Nepal*. Kathmandu: ICIMOD

Mool, PK; Wangda, D; Bajracharya, SR; Kunzang, K; Gurung, DR; Joshi, SP; (2001b) *Inventory of glaciers, glacial lakes, and glacial lake outburst floods: Monitoring and early warning systems in the Hindu Kush-Himalayan region – Bhutan*. Kathmandu: ICIMOD

Mool, PK; Bajracharya, SR (2003) *Inventory of glaciers, glacial lakes and the identification of potential glacial lake outburst floods (GLOFs) affected by global warming in the mountains of Himalayan region: Tista Basin, Sikkim Himalaya, India*. Unpublished project report, with database on CD-ROM, prepared for APN and ICIMOD, Kathmandu

Mool, PK (2005) *Monitoring of glaciers and glacial lakes from 1970s to 2000 in Poiqu Basin, Tibet Autonomous Region, PR China. Unpublished report prepared by* ICIMOD, Kathmandu, Nepal, and CAREERI, Gansu, China

Naito, N; Nakawo, M; Kadota, T; Raymond, CF (2000) 'Numerical simulation of recent shrinkage of Khumbu Glacier, Nepal Himalayas.' *Proceedings of the Debris Covered Glacier Workshop*, held in Seattle, Washington, USA, IAHS Publication No. 264, 2000, pp 245-254. Wallingford (UK): International Association of Hydrological Sciences

Nakawo, M; Fujita, K; Ageta, Y; Shankar, K; Pokharel, AP; Yao, T (1997) 'Basic studies for assessing the impacts of the global warming on the Himalayan cryosphere, 1994-1996.' *Bulletin of Glacier Research* 15: 53-58

Puri, VMK; Singh, RK; Srivastava, D; Sangewar, CV; Swaroop, S; Gautam, CK (1999) 'Inventory of the Himalayan glaciers: A contribution to the International Hydrological Programme. In Kaul, MK (ed) *Geological survey of India*, pp 1-14. Calcutta: Geological Survey of India

Raina, VK; Srivastava, D (2008) *Glacier atlas of India*. Bangalore: Geological Society of India

Reynolds, JM (1999) 'Glacial hazard assessment at Tsho Rolpa, Rolwaling, Central Nepal.' *Quaterly Journal of Engineering Geology* 32: 209-214

Richardson, SD; Reynolds, JM (2000) 'An overview of glacial hazards in the Himalayas.' *Quaternary International* 65/66: 31-47

Roohi, R; Ashraf, R; Naz, R; Hussain, SA; Chaudhry, MH (2005) *Inventory of glaciers and glacial lakes outburst floods (GLOFs) affected by global warming in the mountains of Himalayan region, Indus Basin, Pakistan Himalaya.* Report prepared for ICIMOD, Kathmandu, Nepal

Roohi, R; Ashraf, R; Mustafa N; Mustafa, T (2008) *Preparatory assessment report on community based survey for assessment of glacial lake outburst flood hazards (GLOFs) in Hunza River Basin.* Islamabad: Water Resources Research Iinstitute; National Agricultural Research Centre, Islamabad, and UNDP Pakistan

Sah, M; Philip, G; Mool, PK; Bajracharya, S; Shrestha, B (2005) *Inventory of glaciers and glacial lakes and the identification of potential glacial lake outburst floods (GLOFs) affected by global warming in the mountains of Himalayan region: Uttaranchal Himalaya, India.* Unpublished project report, with database on CD-ROM, prepared for APN and ICIMOD, Kathmandu.

SDMC (2008) *South Asian disaster report 2007: Glacial lake outburst.* New Delhi: SAARC Disaster Management Centre

Shrestha, MS; Bajracharya, SR; Mool, P (2008) *Satellite rainfall estimation in the Hindu-Kush Himalayan Region.* Kathmandu: ICIMOD

Stone, R (2009) 'Peril in the Pamirs.' *Science* 8: 1614-1617

Thorarinsson, S (1939) 'Ice-dammed lakes of Iceland, with particular reference to their value as indicators of glacier oscillations.' *Geografiska Annaler* 21 (3-4): 216-242

Thorarinsson, S (1940) 'The ice-dammed lakes of Iceland.' *Geografiska Annaler* 22: 131-159

Thorarinsson, S (1943) 'Oscillations of the Icelandic glaciers in the last 250 years.' *Geografiska Annaler* 25: 1-54

Thorarinsson, S (1953) 'Some New Aspects of the Grimsvotn Problem.' *Journnal of Glaciology* 2 (14): 267-275

Tshering, N (2008) *An analysis of socio-economic impact and risk mitigation and preparedness of GLOF events in Bhutan: A case study of Samdingkha.* Darwin: UNDP-ECHO

UNDP (2008) 'Capacity building for disaster risk reduction of regional glacial lake outburst floods (GLOF): Preparatory assessment study report - Sutlej Basin, Himachal Pradesh, India.' In *Proceedings of the DIPECHO Interagency Coordination Meeting, September 23, 2008*, New Delhi, India. New Delhi: UNDP and European Commission Humanitarian Aid. www.managingclimaterisk.org/document/India-Preparatory-Assessment-Report-GLOF-Initiative.pdf (accessed April 2010)

UNDP-ECHO (2007a) *Regional GLOF Risk Reduction Project in Bhutan*. Web page from UNDP, New York. www.managingclimaterisk.org/index.php?menu_id=7&submenu_id=112&pagetype_menu=2&content_id=SMN-12 (accessed April 2010)

UNDP-ECHO (2007b) *Regional GLOF Risk Reduction Project in Pakistan*. Web page from UNDP, New York. www.managingclimaterisk.org/index.php?menu_id=7&submenu_id=115&pagetype_menu=2&content_id=SMN-15 (accessed April 2010)

UNDP-ECHO (2007c) *Risk reduction in the Himalayas project: Regional glacial lake outburst floods*. Web page from UNDP, New York. http://managingclimaterisk.org/index.php?menu_id=2&pagetype_menu=2&content_id=MEN-2 (accessed April 2010)

United Nations (2006) *Global Survey of Early Warning Systems*. A report prepared by UNISDR at the request of the Secretary-General of the United Nations. Geneva: UNISDR. www. unisdr.org/ppew/info-resources/ewc3/Global-Survey-of-Early-Warning-Systems.pdf (accessed April 2010)

Vuichard, D; Zimmermann, M (1986) 'The Langmoche flashflood, 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: 91-110

Watanabe, T; Ives, JD; Hammond, JE (1994) 'Rapid growth of a glacial lake in Khumbu Himal, Nepal: Prospects for a catastrophic flood.' *Mountain Research and Development* 14: 329-340

Watanabe, T; Rothacher, D (1996) 'The 1994 Luggye Tsho glacier lake outburst flood, Bhutan Himalaya.' *Mountain Research and Development* 16(1): 77-81

Watanabe, T; Lamsal, D; Ives, JD (2009) 'Evaluating the growth characteristics of a glacial lake and its degree of danger: Imja glacier, Khumbu Himal, Nepal.' *Norwegian Journal of Geography* 63(4): 255-267

WECS (1987) *Study of glacier lake outburst floods in the Nepal Himalaya: Phase 1, Interim report*, May 1987, Report No. 4/1/200587/1/1, Seq. No. 251. Kathmandu: WECS

WECS (1993) *Interim report on the field investigation on the Tsho Rolpa Glacier Lake, Rolwaling Valley,* Report No 3/4/021193/1/1, Seq. No. 436. Kathmandu: WECS

WECS (1994) *Report for the field investigation on the Tsho Rolpa glacier lake, Rolwaling valley*, February 1993- June 1994, WECS N551.489 KAD. Kathmandu: WECS

Wu Lizong; Che Tao; Jin Rui; Li Xin; Gong Tongliang; Xie Yuhong; Mool, PK; Bajracharya, S; Shrestha, B; Joshi, S (2005) *Inventory of glaciers, glacial lakes and the identification of potential glacial lake outburst floods (GLOFs) affected by global warming in the mountains of Himalayan region: Pumqu, Rongxer, Poiqu, Zangbuqin, Jilongcangbu, Majiacangbu, Daoliqu, and Jiazhagangge basins, Tibet Autonomous Region, People's Republic of China.* Unpublished project report, with database on CD-ROM, prepared for APN and ICIMOD, Kathmandu

Xu Daoming (1988) 'Characteristics of debris flow caused by outburst of glacial lake in Boqu River, Xizang, China, 1981.' *GeoJournal* 17:569-580

Yamada, T (1998a) '*Glacier lake and its outburst flood in the Nepal Himalaya,* data center for glacier research, Monograph No 1.' Tokyo: Japanese Society of Snow and Ice, Data Center for Glacier Research

Yamada, T (1998b) 'Monitoring of Himalayan cryosphere using satellite imagery.' In Singh, RB; Murai, S (eds) *Space informatics for sustainable development*, pp 125 -138. New Delhi: Oxford, and IBH Publishing

Annex: Details of lakes identified as critical or 'potentially dangerous'

For details of the data sources and inventory studies see Chapter 2.

Table A1: **Potentially dangerous glacial lakes (tsho) of Bhutan identified in the 2001 inventory and recommended for further investigation and field survey**

Lake No.	Name	Latitude (N)	Longitude (E)	Altitude (masl)	Length (m)	Area (sq.km)
Mo Chu Sub-basin						
Mo_gl 200	Kab	28° 04′ 00.00″	89° 35′ 05.50″	4280	285	0.052
Mo_gl 201		28° 06′ 15.60″	89° 36′ 55.60″	4080	325	0.031
Mo_gl 202		28° 07′ 44.40″	89° 36′ 31.60″	4380	325	0.034
Mo_gl 234	Setang Burgi	28° 10′ 06.00″	89° 51′ 21.10″	4480	795	0.233
Mo_gl 235		28° 08′ 35.40″	89° 50′ 43.00″	4960	565	0.150
Pho Chu Sub-basin						
Pho_gl 84		27° 56′ 48.53″	89° 55′ 14.03″	5040	660	0.214
Pho_gl 148		27° 58′ 09.42″	89° 56′ 16.69″	4880	1285	0.455
Pho_gl 163		28° 06′ 06.43″	89° 54′ 11.83″	4280	1200	0.370
Pho_gl 164	Tarina	28° 06′ 37.22″	89° 54′ 37.81″	4320	1095	0.281
Pho_gl 209	Raphstreng	28° 06′ 43.56″	90° 14′ 03.65″	4360	550	0.146
Pho_gl 210	Luggye	28° 05′ 00.34″	90° 18′ 28.58″	4600	1980	0.770
Pho_gl 211		28° 05′ 40.45″	90° 19′ 11.95″	4710	650	0.142
Pho_gl 313		27° 59′ 58.72″	90° 07′ 18.86″	5030	205	0.222
Mangde Chu Sub-basin						
Mang_gl 99		27° 54′ 22.13″	90° 16′ 45.88″	4960	605	0.193
Mang_gl 106		27° 53′ 19.45″	90° 17′ 33.94″	5040	1480	0.868
Mang_gl 270		27° 58′ 09.32″	90° 20′ 06.98″	5280	850	0.240
Mang_gl 285		28° 00′ 20.90″	90° 19′ 50.77″	5390	795	0.341
Mang_gl 307		28° 02′ 21.01″	90° 21′ 58.87″	5240	1800	0.767
Mang_gl 310		27° 58′ 49.87″	90° 23′ 05.53″	5200	575	0.201
Mang_gl 385		27° 58′ 58.53″	90° 26′ 21.90″	5086	535	0.466
Chamkar Chu Sub-basin						
Cham_gl 198		27° 56′ 22.27″	90° 32′ 15.91″	5046	1495	0.625
Cham_gl 232		27° 59′ 11.33″	90° 30′ 31.42″	5200	565	0.205
Cham_gl 383		28° 01′ 25.91″	90° 42′ 31.77″	4840	2645	1.035
Kuri Chu Sub-basin						
Kuri_gl 172		27° 55′ 47.56″	91°18′ 08.77″		850	0.162

Source: Mool et al. (2001b)

Table A2: **Potentially dangerous glacial lakes in Himachal Pradesh, India based on inventory study of 2004**

Lake No.	Latitude N	Longitude E	Length (m)	Area (sq.km)
beas_gl 39	31°55′01.49″	77°31′51.84″	237.1	0.02
beas_gl 42	31°54′57.44″	77°31′08.62″	178.2	0.02
beas_gl 51	31°40′11.08″	77°37′13.93″	449.8	0.04
beas_gl 54	31°40′15.43″	77°35′57.62″	410.5	0.02
beas_gl 55	31°40′16.02″	77°35′31.67″	311.2	0.03
Satluj_gl 7	31°45′44.73″	78°06′44.25″	262.1	0.03
Satluj_gl 10	32°00′37.86″	78°23′24.62″	384.6	0.06
Satluj_gl 13	32°15′57.63″	78°23′03.14″	325.9	0.03
Ravi_gl 13	32°15′40.69″	76°44′24.84″	278.5	0.06
chenab_gl 7	32°50′05.82″	77°09′17.65″	318.0	0.03
chenab_gl 14	32°34′58.10″	77°11′15.66″	1461.7	0.60
chenab_gl 19	32°33′03.81″	77°31′26.00″	2029.1	0.91
chenab_gl 22	32°47′33.36″	77°22′32.24″	534.2	0.12
chenab_gl 25	32°47′31.43″	77°20′49.55″	429.2	0.12
Sub-basin2 1	32°12′31.98″	78°27′16.29″	513.8	0.05
Sub-basin2 2	32°13′05.47″	78°26′01.32″	414.7	0.05

Source: Bhagat et al. (2004)

Table A3: **Potentially dangerous glacial lakes identified in the inventory study of 2003 and recommended for further investigation and field survey in the Tista river basin, Sikkim Himalayas, India**

Lake No.	Latitude N	Longitude E	Class	Area (sq.km)	Remark
21	27° 32′01.48″	88°05′15.33″	Moraine-dammed	0.29	Thin lateral moraine, supra-glacial lakes, possibility of ice core, two mother hanging glaciers
54	27°49′08.11″	88°15′47.65″	Blocked	0.13	Seems past GLOF event, steep hanging glacier, one side is bounded by rock other by moraine
55	27°49′34.76″	88°15′22.96″	Moraine-dammed	0.10	Thin lateral moraine, supra-glacial lakes side by side
63	27°51′14.76″	88°14′40.23″	Moraine-dammed	0.15	Thin lateral moraine, supra-glacial lakes side by side
70	27°53′44.32″	88°11′33.33″	Moraine-dammed	0.12	High elevation, contact with steep hanging mother glacier
71	27°54′53.26″	88°12′04.89″ 88°09′51.43″	Moraine-dammed	0.59	Seems past GLOF event, high chances of dead ice, clean and debris glacier is in contact with lake
72	27°55′15.53″	88°29′50.13″	Moraine-dammed	0.40	Seems past GLOF event, high chances of dead ice, clean glacier is in contact with lake
109	28°00′26.98″		Moraine-dammed	0.35	Thin lateral moraine and steep hanging glacier
120	28°00′32.65″	88°34′33.65″	Valley	0.27	Around 400m downstream of gl 121
121	28°00′59.42″	88°33′56.00″	Moraine-dammed	0.20	Thin lateral moraine and steep hanging glacier
127	27°59′34.95″	88°49′18.78″	Moraine-dammed	1.59	3km and 600m wide, associated with supra-glacial lakes at the toe and valley glacier
142	28°01′35.08″	88°42′58.63″	Moraine-dammed	1.07	Around 600m downstream of gl 143
143	28°00′34.46″	88°42′16.28″	Blocked	0.65	Blocked by glacier moraine and the distance of the glacier is less than 200m
195	27°51′56.13″	88°52′12.84″	Moraine-dammed	0.11	Attached with steep hanging glacier

Source: Mool et al. (2003).

Table A4: **Potentially dangerous glacial lakes of Nepal identified from the inventory and recommended for further investigation and field survey in 2001**

Lake No	Lake name	Latitude N	Longitude E	Altitude (masl)	Length (m)	Area (sq.km)	Remarks
Tamor Sub-basin							
Ktr_gl 192 (A)	Nagma Pokhari	27° 52.10′	87° 52.02′	4,907	210	0.150	Burst on 23 June 1980
Ktr_gl 146 (B)	Unnamed	27° 48.83′	87° 45.09′	4,876	830	0.181	
Arun Sub-basin							
(C)	Lower Barun	27° 45.31′	87° 06.31′	4,550	1,100	0.666	
Dudh Koshi Sub-basin							
Kdu_gl 28 (D)	Lumding Tsho	27° 46.51′	86° 37.53′	4,846	625	0.105	
Kdu_gl 350 (E)	Imja Tsho	27° 54.00′	86° 55.40′	5,023	410	0.049	
Kdu_gl 399 (F)	Tam Pokhari	27° 44.33′	86° 50.76′	4,431	515	0.139	GLOF, 3 Sept 1998
Kdu_gl 422 (G)	Dudh Pokhari	27° 41.21′	86° 51.68′	4,760	1,120	0.274	
Kdu_gl 442 (H)	Unnamed	27° 47.70′	86° 54.81′	5,266	840	0.134	
Kdu_gl 444 (I)	Unnamed	27° 48.23′	86° 56.61′	5,056	420	0.112	
Kdu_gl 449 (J)	Hungu	27° 50.17′	86° 56.26′	5,181	875	0.199	
Kdu_gl 459 (K)	East Hungu 1	27° 47.92′	86° 57.95′	5,379	465	0.079	
Kdu_gl 462 (L)	East Hungu 2	27° 48.30′	86° 58.65′	5,483	640	0.212	
Kdu_gl 464 (M)	Unnamed	27° 46.86′	86° 57.22′	5,205	1,100	0.349	
Kdu_gl 466 (N)	West Chamjang	27° 45.24′	86° 57.33′	4,983	125	0.006	Kdu-gl 465 to 469 merged into one
Kdu_gl 55 (O)	Dig Tsho	27° 52.41′	86° 36.61′	4,364	605	0.143	GLOF, 4 Aug 1985
Tamakoshi Sub-basin							
Kta_gl 26 (P)	Tsho Rolpa	27° 52.03′	86° 28.41′	4,556	1,070	0.232	Kta_gl 26 to 32 merged
Budhi Gandaki Sub-basin							
Gbu_gl 9 (Q)	Unnamed	28° 35.79′	84° 38.09′	3,590	230	0.082	
Marsyangdi River Sub-basin							
Gmar_gl 70 (R)	Thulagi	28° 29.69′	84° 29.01′	3,825	420	0.223	
Kali Gandaki Sub-basin							
Gka_gl 38 (S)	Unnamed	29° 2.76′	83° 40.52′	5,419	600	0.149	
Gka_gl 67 (T)	Unnamed	29° 12.79′	83° 41.79′	5,452	3,610	1.013	

Source: Mool et al. (2001a)

Table A5: **Prioritisation of potentially dangerous glacial lakes of Nepal identified in 2009 study**

Name	ID No., in 2001 study	ID No. 2009 study	Category
Tsho Rolpa	kta_gl_26	kota_gl_0009	I
Lower Barun		koar_gl_0009	I
Imja	kdu_gl_350	kodu_gl_0184	I
Lumding	kdu_gl_28	kodu_gl_0036	I
West Chamjang	kdu_gl_467	kodu_gl_0242	I
Thulagi (Dona)	gmar_gl_70	gamar_gl_0018	I
Nagma	ktr_gl_192	kotr_gl_0133	II
Hungu	kdu_gl_464	kodu_gl_0241	II
Tam Pokhari	kdu_gl_399	kodu_gl_0193	II
Hungu	kdu_gl_449	kodu_gl_0229	II
*		kotr_gl_0191	III
*		gaka_gl_0004	III
Barun*	kar_gl_29	koar_gl_0012	III
*	kdu_gl_460	kodu_gl_0238	III
(Q)	gbu_gl_9	gabu_gl_0009	III
(H)	kdu_gl_442	kodu_gl_0220	III
*	kar_gl_30	koar_gl_0016	III
(S)	gka_gl_38	gaka_gl_0008	III
(B)	ktr_gl_146	kotr_gl_0111	III
East Hungu 2	kdu_gl_462	kodu_gl_0239	III
Kaligandaki (T)	gka_gl_67	gaka_gl_0022	III

Source: ICIMOD 2009, unpublished
*Not listed as potentially dangerous in the 2001 inventory

Table A6: **Potentially dangerous glacial lakes in the Indus Basin, Pakistan, identified from the inventory survey in 2002-2005**

Lake type	Lake No.	Total Area (sq.km)	Associated Glacier	Distance to glacier (m)	Remarks
End Moraine	Swat_gl28	0.22	Swat_gr21	-	In contact with large glacier source
End Moraine	Swat_gl189	0.27	-	-	Near massive glacier source
End Moraine	Chitr_gl61	0.05	Chitr_gr108	-	In contact with mountain glacier
End Moraine	Gil_gl550	0.10	Gil_gr191	464	Followed by large glacier source
End Moraine	Gil_gl590	0.19	Gil_gr366	-	In contact with large hanging glacier
End Moraine	Gil_gl505	0.21	Gil_gr79	820	Massive hanging glacier source
End Moraine	Gil_gl336	0.21	Gil_gr22	225	Near to hanging glacier source
End Moraine	Gil_gl469	0.27	-	375	Near massive mountain glacier
End Moraine	Gil_gl399	0.73	Gil_gr28	-	In contact with hanging glaciers
Valley	Gil_gl589	0.20	-	412	Near several hanging glaciers
Valley	Gil_gl611	0.29	-	159	Near several hanging glaciers
End Moraine	Hunza_gl6	0.12	Hunza_gr119	175	Associated glacier Passu with area of 62.9 sq.km
End Moraine	Shyk_gl60	0.08	Shyk_gr345	-	In contact with hanging glacier
End Moraine	Shyk_gl62	0.09	Shyk_gr355	-	In contact with large glacier
End Moraine	Shyk_gl45	0.13	Shyk_gr293	-	In contact with large glacier
End Moraine	Shyk_gl65	0.21	Shyk_gr361	-	Large glacier source
Valley	Shyk_gl64	0.11	Shyk_gr360	432	Preceded by a lake and large glacier

Table A6 Con...

Lake type	Lake No.	Total Area (sq.km)	Associated Glacier	Distance to glacier (m)	Remarks
Valley	Shyk_gl51	0.17	Shyk_gr305	435	Large glacier source
Cirque	Ind_gl125	0.14	Ind_gr213	-	In contact with hanging glacier
Cirque	Ind_gl502	0.15	-	-	Near hanging ice mass
Cirque	Ind_gl519	0.17	Ind_gr928	-	Large lake near hanging glacier
Cirque	Ind_gl162	0.27	Ind_gr313	-	In contact with hanging glacier
End Moraine	Ind_gl394	0.03	Ind_gr656	-	In contact with larger glacier
End Moraine	Ind_gl444	0.04	Ind_gr878	-	In contact with hanging glacier
End Moraine	Ind_gl457	0.06	Ind_gr886	177	Near hanging glacier
End Moraine	Ind_gl47	0.11	Ind_gr166	-	Near hanging glacier
End Moraine	Ind_gl160	0.12	Ind_gr311	-	Near hanging glacier
End Moraine	Ind_gl290	0.13	Ind_gr470	-	In contact with hanging glacier
End Moraine	Ind_gl351	0.14	-	-	Snow avalanche source
End Moraine	Ind_gl41	0.17	Ind_gr165	505	Large lake near hanging glacier
End Moraine	Ind_gl135	0.24	Ind_gr263	450	Near hanging glacier
End Moraine	Ind_gl147	0.28	Ind_gr295	388	Near hanging glacier
Valley	Ind_gl130	0.11	Ind_gr245	472	Near hanging glacier
Cirque	Shin_gl75	0.25	Shin_gr85	-	In contact with hanging glacier
End Moraine	Shin_gl115	0.13	Shin_gr89	180	Near hanging glacier
End Moraine	Shin_gl167	0.07	Shin_gr118	-	In contact with hanging glacier
End Moraine	Shin_gl220	0.05	Shin_gr151	-	Lake in contact with hanging glacier
Valley	Shin_gl227	0.08	Shin_gr157	200	Near hanging glacier source
Cirque	Astor_gl36	0.05	Astor_gr199	-	Hanging glacier source
Cirque	Astor_gl48	0.07	Astor_gr250	-	Snow avalanche source
Cirque	Astor_gl51	0.11	Astor_gr254	-	Hanging glacier source
Cirque	Astor_gl25	0.14	Astor_gr163	-	In contact with hanging glacier
Cirque	Astor_gl40	0.16	Astor_gr218	-	Hanging glacier source
End Moraine	Astor_gl53	0.08	Astor_gr254	75	Close to large glacier
End Moraine	Astor_gl121	0.09	Astor_gr564	-	At active glacier tongue
End Moraine	Astor_gl108	0.16	Astor_gr445	-	In contact with large glacier
Valley	Astor_gl50	0.31	Astor_gr252	125	Situated in hanging valley, dangerous glacial lake 300m upstream
Cirque	Jhe_gl97	0.20	-	-	In contact with large glacier
Cirque	Jhe_gl113	0.12	Jhe_gr200	-	In contact with hanging glacier
Cirque	Jhe_gl134	0.24	Jhe_gr315	-	Snow avalanche source
End Moraine	Jhe_gl131	0.71	Jhe_gr300	153	Near hanging glacier
End Moraine	Jhe_gl140	0.12	-	-	In contact with hanging glacier

Source: Roohi et al. 2005

Acronyms and Abbreviations

APN	Asia-Pacific Network for Global Change Research
ASAR	Advanced Synthetic Aperture Radar
CAREERI	Cold and Arid Regions Environmental and Engineering Research Institute
CAS	Chinese Academy of Sciences
DEM	digital elevation model
DGM	Department of Geology and Mines, Bhutan
DHM	Department of Hydrology and Meteorology, Government of Nepal
ESA	European Space Agency
ETM+	Enhanced Thematic Mapper plus of Landsat system
EWS	early warning system
GFDRR	Global Facility for Disaster Reduction and Recovery
GIS	geographical information system
GLIMS	Global Land Ice Measurements from Space
GLOF	glacial lake outburst flood
HKH	Hindu Kush-Himalayas/n
ICIMOD	International Centre for Integrated Mountain Development
JICA	Japan International Cooperation Agency
LANDSAT	Land Observation Resources Satellite (Landsat)
MCC	Meteor Communication Corporation
NASA	National Aeronautics and Space Administration
NRSC	National Remote Sensing Centre, Hyderabad
SAR	Synthetic Aperture Radar
Sida	Swedish International Development Cooperation Agency
SRTM	Shuttle Radar Transmission Mission
START	global change SysTem for Analysis, Research and Training
TM	Thematic Mapper (Landsat)
TU	Tribhuvan University, Nepal
UNDP	United Nations Development Programme
UNEP/ RRC-AP	United Nations Environment Programme/ Regional Resources Centre for Asia and the Pacific
UNISDR	United Nations International Strategy for Disaster Reduction
WECS	Water and Energy Commission Secretariat
WWF	World Wildlife Fund

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About ICIMOD

The International Centre for Integrated Mountain Development, ICIMOD, is a regional knowledge development and learning centre serving the eight regional 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. We support regional transboundary programmes through partnership with regional partner institutions, facilitate the exchange of experience, and serve as a regional knowledge hub. We strengthen networking among regional and global centres of excellence. Overall, we are working 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 billions of people living downstream – now, and for the future.

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