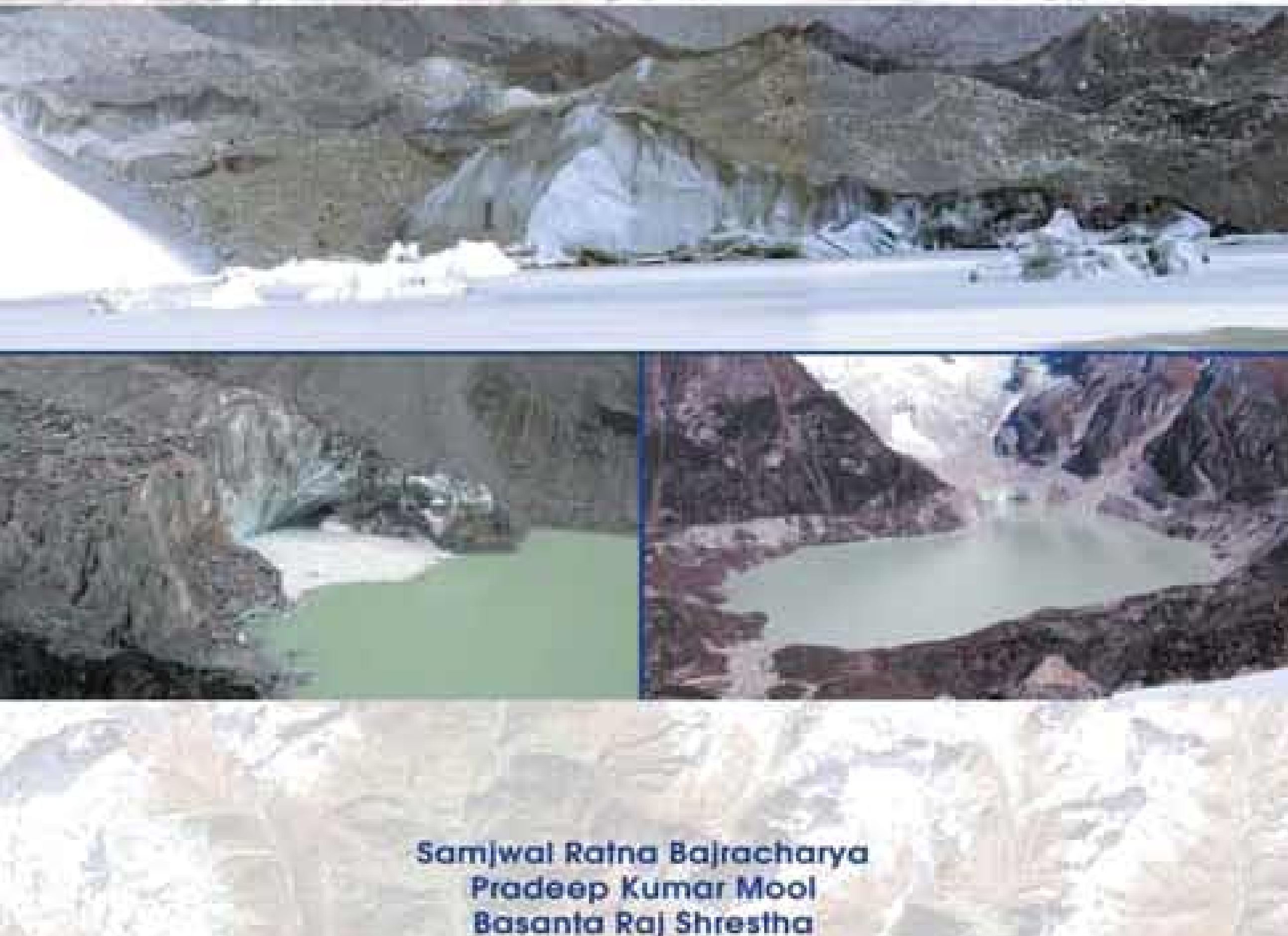
Impact of Climate Change on Himalayan Glaciers and Glacial Lakes

Case Studies on GLOF and Associated Hazards in Nepal and Bhutan



Samjwal Ratna Bajracharya
Pradeep Kumar Mool
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The **International Centre for Integrated Mountain Development** (ICIMOD) is an independent 'Mountain Learning and Knowledge Centre' serving the eight countries of the Hindu Kush-Himalayas – Afghanistan, Bangladesh, Bhutan, China, India, Myanmar, Nepal and Pakistan – and the global mountain community. Founded in 1983, ICIMOD is based in Kathmandu, Nepal, and brings together a partnership of regional member countries, partner institutions, and donors with a commitment for development action to secure a better future for the people and environment of the extended Himalayan region. ICIMOD's activities are supported by its core programme donors: the governments of Austria, Denmark, Germany, Netherlands, Norway, Switzerland, and its regional member countries, along with over thirty project co–financing donors. The primary objective of the Centre is to promote the development of an economically and environmentally sound mountain ecosystem and to improve the living standards of mountain populations.

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Foreword

Director General
International Centre for Integrated Mountain Development

The Himalayas have the largest concentration of glaciers outside the polar region. These glaciers are a freshwater reserve; they provide the headwaters for nine major river systems in Asia – a lifeline for almost one-third of humanity. There is clear evidence that Himalayan glaciers have been melting at an unprecedented rate in recent decades; this trend causes major changes in freshwater flow regimes and is likely to have a dramatic impact on drinking water supplies, biodiversity, hydropower, industry, agriculture and others, with far-reaching implications for the people of the region and the earth's environment. One result of glacial retreat has been an increase in the number and size of glacial lakes forming at the new terminal ends behind the exposed end moraines. These in turn give rise to an increase in the potential threat of glacial lake outburst floods occurring. Such disasters often cross boundaries; the water from a lake in one country threatens the lives and properties of people in another. Regional cooperation is needed to formulate a coordinated strategy to deal effectively both with the risk of outburst floods and with water management issues.

The International Centre for Integrated Mountain Development (ICIMOD) in partnership with UNEP and the Asia Pacific Network and in close collaboration with national partner organisations documented baseline information on the Himalayan glaciers, glacial lakes, and GLOFs in an earlier study which identified some 200 potentially dangerous glacial lakes in the Himalayas. The study published here builds upon these past initiatives and investigates the impact of climate change on selected glaciers and glacial lakes.

The publication provides an account of glacier retreat and growth of glacial lakes in two selected river sub-basins, one in Nepal and one in Bhutan. It describes important methodological aspects of assessing the vulnerability for GLOF hazards based on empirical data and evidence. It also investigates the possibility of devising a method for regular temporal monitoring of glacial lakes in remote and inaccessible mountain locations using satellite-based techniques. The results provide a basis for the development of monitoring and early warning systems and planning and prioritisation of disaster mitigation efforts that could save many lives. The report also provides useful information for those concerned with water resources and environmental planning.

This report is also being packaged in a multi-media CD-ROM with films, 3-D visualisation photographs, and satellite images. The report and multimedia product will be useful for scientists, planners, and decision makers, as well as for raising the awareness of the public at large to the potential impacts of climate change in the Himalayas. With this information, we hope to contribute to improving the lives of mountain people and help safeguard future investments in the region. It highlights the need to replicate, refine, and scale up such studies, using scientific approaches and empirical evidence, in other parts of the Himalayan region. We are convinced that it will increase the awareness of the readers of the need to support initiatives.

ICIMOD is grateful to the United Nations Environment Programme Regional Office for Asia and the Pacific (UNEP/ROAP) for its support for this work. We are also pleased that the project has enabled us to continue to strengthen our collaboration with the Royal Government of Bhutan's Department of Geology and Mines and to continue to assist in developing regional capacity and co-operation. We are grateful to the European Space Agency (ESA) for providing satellite images for regular temporal monitoring of the Imja glacial lake in Nepal. Finally, I wish to thank the authors and many contributors for preparing this timely and relevant report at a time when the issue of climate change is being hotly debated in the international arena. We hope that this report will serve as a milestone for studying the impact of climate change in the Himalayas.

Dr. Andreas Schild
Director General
ICIMOD

Foreword

Executive Director
United Nations Environment Programme

Glaciers are one of the most sensitive indicators of climate as they grow and shrink in response to the changing air temperature. The glaciers of the Hindu Kush–Himalaya (HKH) are nature's renewable storehouse of fresh water from which hundreds of millions of people downstream benefit just when it is most needed during the dry hot season before the start of monsoon. Understanding the pattern of snow accumulation and melting is therefore important for the appropriate utilization of this Himalayan water resource. Observing glacier advancement and recession is also important as it can assist in identifying and thus mitigating mountain disasters in order to safeguard the livelihoods of vulnerable mountain people and their downstream neighbors.

Climate change in the Himalayas: Monitoring of Glaciers and Glacial Lakes is one of the outputs under the Bali Strategic Plan for Technology Support and Capacity Building. The Bali Strategic Plan, adopted by 23rd session of UNEP Governing Council in 2005 provides an opportunity for developing countries and countries in economic transition to coherently address the needs, priorities and responsibilities in the field of environment.

The book is built upon the research which UNEP supported during 1999 – 2001, where comprehensive inventory and a geographic information system (GIS) database of glaciers and glacial lakes in Nepal and Bhutan were prepared using available maps, satellite images, aerial photographs, reports, and field studies. This report includes a description of the methods used to identify glaciers and glacial lakes, including those that are potentially dangerous. It is complemented by an inventory and maps of the glaciers and glacial lakes in Nepal and Bhutan. The book includes a summary of the results of studies of various glacial lakes and a brief review of the causes and effects of known glacial lake outburst floods or GLOF events in Nepal and Bhutan.

I am sure that this comprehensive report and digital database will be of service to all the scientists, planners and decision-makers working in and outside the region in this field. Through informed actions, we hope it will contribute to improving the lives of those living in the mountains and help safeguard future investments, such as infrastructure for the benefit of people in the region.

UNEP is grateful to the International Centre for Integrated Mountain Development (ICIMOD) for carrying out this important project and to both national governments concerned for their valuable support and advice. We are also pleased that this project has enabled us to continue and strengthen our collaboration in assisting to develop regional capacity with the Department of Hydrology and Meteorology (Government of Nepal) and the Department of Geology and Mines, Ministry of Trade and Industry (Royal Government of Bhutan).

Achim Steiner
United Nations Under-Secretary General
and Executive Director
United Nations Environment Program

Preface

In the face of global warming, most Himalayan glaciers have been retreating at a rate that ranges from a few metres to several tens of metres per year, resulting in an increase in the number and size of glacial lakes and a concomitant increase in the threat of glacial lake outburst floods (GLOFs). Such climate changes have ultimate effects on the life and property of the mountain people living downstream. While the effect of human activity on global climate is still being hotly debated, the retreat of glaciers in the Himalaya is compelling evidence of the need for action on climate change.

Approximately 15,000 glaciers (covering an area of 33,340 sq.km), and 9000 glacial lakes throughout Bhutan, Nepal and Pakistan, as well as selected river basins in China and India were documented in a baseline study conducted earlier by ICIMOD, UNEP, and the Asia Pacific Network for Global Change Research (APN). Twenty-one GLOF events have adversely affected Nepalese territory in the recent past and to date over 200 potentially dangerous glacial lakes have been documented across the Himalayan region. These facts underline the urgent need to enhance scientific knowledge of glacier environments by continuously monitoring glaciers and glacial lakes, carrying out vulnerability assessments, implementing mitigation and adaptation mechanisms, and developing a glacial lake outburst flood (GLOF) early warning system. Regional co-operation to develop a coordinated strategy to deal with trans-boundary issues related to the impacts which can occur as a result of climate change is also required.

This publication focuses on the effects of climate change on glaciers and glacial lakes in two hotspots of glacial activity in the Himalaya: the Dudh Koshi sub-basin of Nepal and the Pho Chu sub-basin of Bhutan. Both these basins have witnessed devastating GLOF events in the recent past. The GLOFs at Dig Tsho in 1985 (Nepal) and Luggye Tso in 1994 (Bhutan) are considered 'textbook' case studies of GLOF events and have drawn the attention of researchers world-wide. A multi-media CD-ROM is being prepared as a companion to this book and will be helpful in raising awareness about the sensitivity of climate change to policy- and decision-makers, the concerned scientific community, and the general public. These materials will be helpful in designing mitigation measures to help safeguard human lives and valuable infrastructure in hazardous river valleys.

While this and other activities are helping to raise awareness of the risks posed by GLOFs, it will also be essential to replicate these studies and to continue to extend them systematically to include other high-risk areas in the Himalaya. The scientific modelling approaches and the empirical methods discussed here are both needed first steps that will be valuable in refining and scaling up this type of investigation to other Himalayan hot-spots. What is needed now is urgent action by the international community to help develop even better scientific understanding of the consequences of global climate change and to take the corrective and precautionary measures before it is too late.

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Acknowledgements

This book is an outcome of an ICIMOD project on ‘Capacity building and early warning activities on GLOF’ and a part of the Bali Strategic Plan (BSP) for Technology Support and Capacity-building adopted in Bali, Indonesia, on 4 December 2004 by the Intergovernmental Working Group. The United Nations Environment Programme (UNEP) Regional Office Asia and the Pacific also supported this project.

We are grateful to Deo Raj Gurung, Karma Toeb, and Tashi Gyalmo from the Department of Geology and Mines, Ministry of Trade and Industry of Bhutan, who were actively engaged in the project particularly in the field studies and photography in Bhutan. Thanks also go to the Director General of the Department of Geology and Mines, Dorji Wangda, for kind cooperation and support while implementing the project. We thank Pravin Raj Maskey, Ministry of Water Resources, and Sharad Prasad Joshi, Water and Energy Commission Secretariat, Government of Nepal, for their support in the GLOF modelling of the Raphstreng Tso, Bhutan, for helping to draft part of the Terrain Classification in Chapter 5, and for their fieldwork in the Khumbu region. Thanks also go to ICIMOD colleagues Arun Shrestha, Birendra Bajracharya, and Lokap Rajbhandari for GLOF modelling of Imja Tsho.

Our sincere thanks also go to the former Director General of ICIMOD, J. Gabriel Campbell, for supporting the beginning of this project and to Andreas Schild, present Director General of ICIMOD, for seeing it through to its completion.

We would also like to thank Jean Charles and Jürg Lichtenegger of the EDUSPACE Operational Team for providing the European Space Agency RADAR satellite images monthly-basis through the ENVISAT Project to ICIMOD; this data was used for the temporal monitoring of Lake Imja Tsho for 1st-stage early warning.

Thanks also go to Vishnu Dangol, Tribhuvan University, and Jürg Lichtenegger for reviewing the manuscript and making valuable comments. We are also indebted to Megh Raj Dhital (Tribhuvan University), and Richard L. Armstrong (National Snow and Ice Data Centre) for their critical review of the manuscript; and to the editors A. Beatrice Murray (ICIMOD) and Isabella C. Bassignana Khadka (consultant) for helpful insights. A heartfelt thanks to the layout persons (Dharma Ratna Maharjan and Gauri Dangol) for their hard work in preparing this manuscript in a very short time.

We would also like to thank Monica Moktan for office assistance and Bidya Banmali Pradhan for coordinating the project processes with UNEP/ROAP. Last but not least, we wish to thank Surendra Shrestha, Regional Director of UNEP/ROAP for his timely and strong support and advice while implementing the project.

Executive Summary

The global mean temperature is expected to increase between 1.4 to 5.8ºC over the next hundred years. The consequences of this change in global climate are already being witnessed in the Himalayas where glaciers and glacial lakes are changing at alarming rates. Himalayan glaciers are retreating at rates ranging from 10 to 60m per year and many small glaciers (<0.2 sq.km) have already disappeared. Our study shows that the terminus of most of the high altitude valley glaciers in Bhutan, China, and Nepal are retreating very fast; vertical shifts as great as 100m have been recorded during the last fifty years and retreat rates of 30m per year are common. As glaciers retreat, glacial lakes grow, and many Himalayan basins are reporting very fast growing lakes. A remarkable example is Lake Imja Tsho in the Dudh Koshi sub-basin (Khumbu–Everest region); while this lake was virtually nonexistent in 1960, it now covers nearly 1 sq.km and the Imja glacier which feeds it is retreating at an unprecedented 74m per year (between 2001 and 2006). Similar observations were made in the Pho Chu basin of the Bhutan Himalaya, where the change in size of some glacial lakes has been as high as 800 per cent over the past 40 years. At present, several supraglacial ponds on the Thorthormi glacier are growing quickly and merging. These lakes pose a threat because of their proximity to other large glacial lakes in the Pho Chu sub-basin where, in a worst-case glacial lake outburst flood (GLOF) scenario, they could cascade on to these other lakes with catastrophic consequences.

The study stresses the importance of methodologies used to assess glacier retreat, the expansion of glacial lakes and the impact of GLOFs. The hydrological modelling of glacial lakes, terrain classification, and vulnerability assessment are important scientific means to understand GLOF impacts. They help in devising mitigation measures and early warning systems. A dam-breach model developed by the National Weather Services (NWS-BREACH) was used to simulate the outburst hydrographs of Lakes Imja Tsho in Nepal and Raphstreng Tso in Bhutan. The model provides information on discharge and flood arrival time in downstream areas.

Based on observations of damage caused by the Dig Tsho GLOF of 1985, the vulnerability of various terrain units in the vicinity of a possible Imja Tsho GLOF was assessed. This terrain classification scheme provided valuable information on the possible extent of the damage to be expected in the event of an Imja Tsho GLOF. The vulnerability analysis in the Imja and Dudh Koshi valleys indicated that the upper terrace of the Syomare village as well as lower terraces identified in Ghat, Chutawa, Chermading, Phakding, Benkar, Tawa, and Jorsalle villages could be severely damaged by a GLOF event at Lake Imja Tsho.

GLOF mitigation measures and early warning systems applied in the Nepal and Bhutan Himalayas are also discussed. Such techniques are quite expensive and require much detailed field-work and maintenance, an alternative, which is being considered in a feasibility study, is regular temporal monitoring of glacial lakes by RADAR satellite-based techniques to detect any changes and provide an early warning.

Acronyms and Abbreviations

C-type	clean or debris free glacier
Cham_gl	chamkhar Chu glacial lake
D-type	debris covered glacier
DEM	digital elevation model
DHM	Department of Hydrology and Meteorology
etm	enhanced thematic mapper
GLOF	glacial lake outburst flood
HKH	Hindu Kush-Himalayas/n
ICIMOD	International Centre for Integrated Mountain Development
IPCC	Intergovernmental Panel on Climate Change
Kdu_gl	Dudh Koshi glacial lake
Kdu_gr	Dudh Koshi glacier
Kuri_gl	Kuri Chu glacial lake
Landsat	Land Resources Satellite
LISS	Linear Imaging and Self-Scanning Sensor (IRS)
Magd_gl	Mangde Chu glacial lake
MCC	Meteor Communication Corporation
MOS	Marine Observation Satellite
Mo_gl	Mo Chu glacial lake
MSS	Multi Spectral Scanner (Landsat)
'n'	Manning's roughness coefficient
Pho_gl	Pho Chu glacial lake
ppm	parts per million
ROAP	Regional Office Asia and the Pacific
UNEP	United Nations Environment Programme
USGS	United States Geological Survey
WECS	Water and Energy Commission Secretariat
WHO	World Health Organisation
WMO	World Meteorological Organisation

Impact of Climate Change on Glaciers and Glacial Lakes

Chapter 1
Introduction

Global climate change occurs naturally and periodically and is often attributed to continental drift, variations in the earth's axis and orbit, variations in solar energy output and the frequency of volcanic activity. The average surface temperature of the earth has been increasing since the end of the Little Ice Age (15th–18th centuries). Over the past few decades, human activities have significantly altered the atmospheric composition, causing a climate change not previously experienced. The average surface temperature of the earth has increased between 0.3ºC and 0.6ºC over the past hundred years and the increase in global temperature is predicted to continue rising during the 21st century. On the Indian sub-continent, temperatures are predicted to increase between 3.5 and 5.5ºC by 2100 (IPCC 2001a) and an even greater increase is predicted for the Tibetan Plateau (Lal 2002). It is estimated that a 1ºC rise in temperature will cause alpine glaciers worldwide to shrink as much as 40 per cent in area and more than 50 per cent in volume as compared to 1850 (IPCC 2001b; CSE 2002).

The Himalayas are an extraordinarily high mountain chain, spanning 2500 km east to west across five countries and encompassing many varied cultures and an extensive diversity of flora and fauna. The glaciers of the Hindu Kush–Himalayan (HKH) region are one of nature's greatest renewable storehouses of fresh water; properly utilised, they benefit hundreds of millions of people downstream. A study carried out jointly by ICIMOD, UNEP, and Asia-Pacific Network for Global Change Research (APN) between 1999 and 2003 documented about 15,000 glaciers and 9000 glacial lakes in Bhutan, Nepal, Pakistan and selected basins of China and India (Mool et al. 2005b; Figure 1.1). Such a high concentration of captive water and ice has aptly earned the Himalayan region the designation 'Third Pole' (Dyhrenfurth 1955). This mountain range feeds most of the major perennial river systems in the region and is considered the lifeline for approximately 10 per cent of the world's population.

Today, glaciers in the region are retreating, this is compelling evidence of global climate change; if the trend continues, a long-term loss of natural fresh water storage is predicted to be dramatic. As glaciers retreat, lakes commonly form behind the newly exposed terminal moraine. The rapid accumulation of water in these lakes can lead to a sudden breach of the moraine dam. The resultant rapid discharge of huge amounts of water and debris is known as a glacial lake outburst flood (GLOF) — and the results can be catastrophic to the downstream riparian area (Richardson and Reynolds 2000). Every country within the Himalayan region has at some time or other suffered a glacial lake outburst flood event. Records show 15 GLOF events recorded in Nepal, 6 in the Tibet Autonomous Region of China (with consequences for Nepal) and 5 in Bhutan. According to Yamada (1998), WECS (1987) and Mool (2001a,b), the following GLOFs have occurred in Nepal since 1970: Nare (1977), Nagma Pokhari (1980), Dig Tsho (1985), Chhubung (1991), and Tam Pokhari (1998). The Zhangzhangbo (1981) and Jinco (1982) GLOFs occurred in the Tibet Autonomous Region of China; and the Luggye Tso GLOF (1994) occurred in Bhutan (Watanabe and Rothacher 1996; Geological Survey of Bhutan 1999; Gansser 1970).

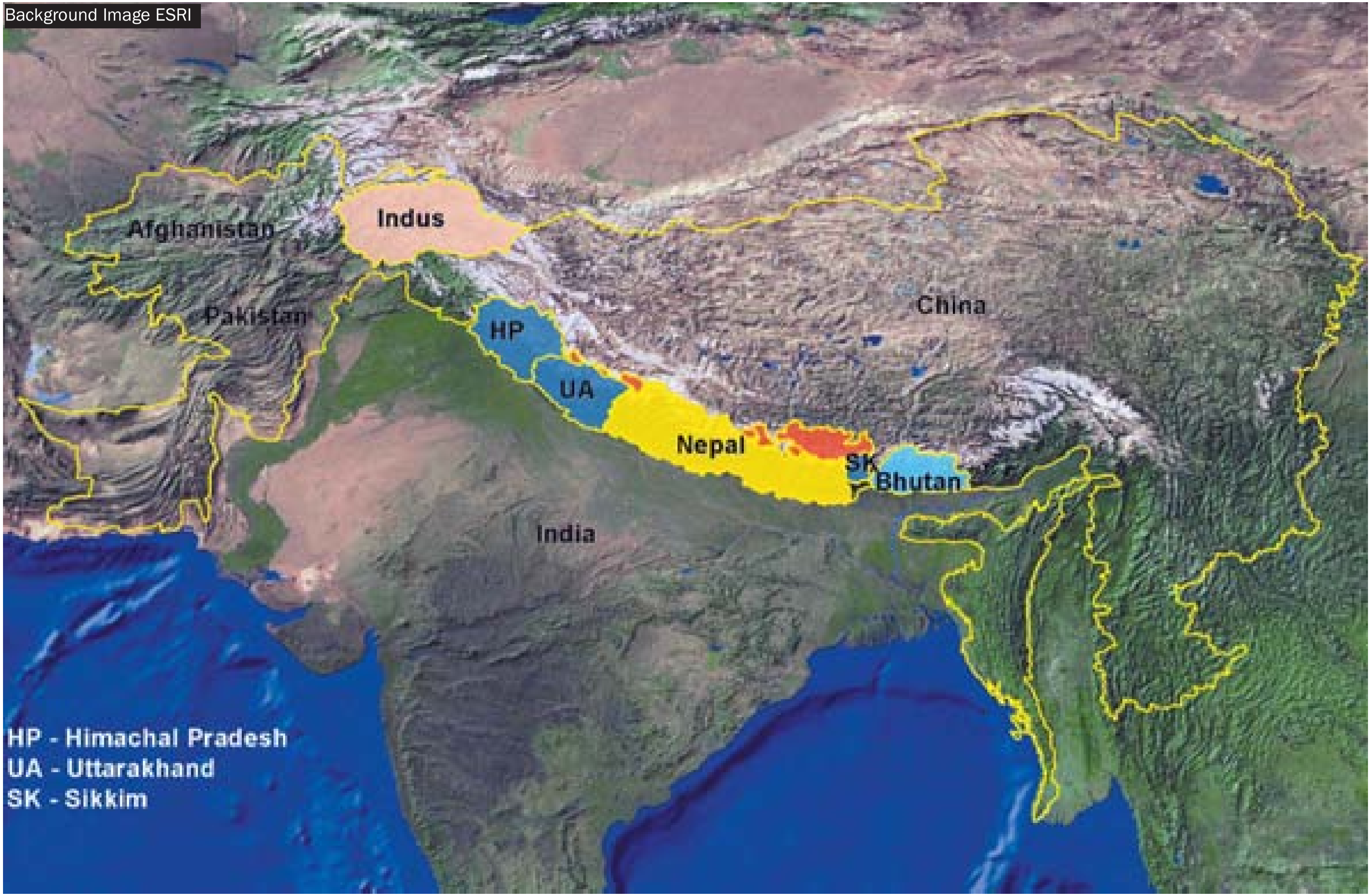


Figure 1.1: Location map of glaciers and glacial lakes studied in Bhutan, Nepal, India, Pakistan, and China during the ICIMOD, UNEP, and APN Project of 1999-2003

The Zhangzhangbo GLOF of 1981 caused damage in the Zhangzangbo and Sun Koshi valleys. It destroyed the Sun Koshi Power Station and the Friendship Bridge at the Nepal-China border, as well as two other bridges and devastated extensive sections of the Arniko Highway; losses totalled more than US $3 million (XuDaoming 1985; Mool et al. 2001a). Four years later, the Dig Tsho GLOF occurred and destroyed the nearly completed Namche Hydropower Plant (with an estimated loss of US $1.5 million), 14 bridges, trails, and cultivated land, and cost many lives. This unprecedented degree of damage and property loss attracted the attention of different government and non-government organisations. The systematic study of glacial lakes in Nepal began at the Water and Energy Commission Secretariat (WECS) in 1985, (WECS 1987, Yamada 1998). Similarly, the 1994 Luggye Tso GLOF in Bhutan, which damaged the sacred Punakha Dzong, ravaged much cultivated land, and killed over 20 people, prompted the Royal Government of Bhutan to take action. Bhutan's Department of Geology and Mines (DGM) subsequently undertook a study of the glacial lakes.

Glaciers and glacial lakes abound in the Himalayas; Chapter 2 reviews the status of Himalayan glaciers in China, India, Bhutan, and Nepal. Recent studies by ICIMOD show that glaciers in the Dhud-Koshi sub-basin of Nepal are retreating at unpredicted rates; glacier retreat rates of 10 to 60m per year and, in exceptional cases, as fast as 74m per year, have been recorded.

Regular monitoring of potentially dangerous glacial lakes at high risk for GLOF events is essential. Mool et al. (2001a,b) documented 24 potentially dangerous glacial lakes in Bhutan and 20 in Nepal. Out of these, eight lakes are located in the Pho Chu basin of Bhutan and twelve in the Dudh Koshi sub-basin of Nepal. These two basins have the highest concentration of glacial lakes in their respective countries. Chapter 3 focuses on glacial lakes in these two sub-basins; with the highest concentration of glacial lakes they are also 'hot spots' for potential GLOF activity. Lake Imja Tsho in Nepal and Lake Raphstreng Tso in Bhutan are discussed in detail.

Hazard assessment, especially in those river valleys that are known to be potentially at risk for GLOF events, is essential in developing the most appropriate responses and mitigation measures. Hydrodynamic dam breach modelling can help in understanding flood height, flood routing, and potential discharge from a likely GLOF event. Lakes Imja Tsho and Luggye Tso were selected for modelling analysis and the results are discussed in Chapter 4.

While GLOF modelling can give some useful insights it is helpful to supplement these both with data gathered from previous GLOF events and with field data. The study of past GLOF affected areas allows classification of various terrain units. This type of classification assesses the extent of damage sustained by a particular terrain unit after a GLOF event and uses that information to predict what damage subsequent GLOFs might cause, information that can then be incorporated into hazard maps. Chapter 5 discusses the terrain classification of the Langmoche valley where the Dig Tsho GLOF occurred in 1985 and shows that a similar classification scheme can be applied in the Imja valley.

Mitigation measures may help to prevent a GLOF event and/or reduce the severity of its impact. Early warning systems, including satellite-based and other techniques, are helpful in reducing the threat that GLOFs pose to people in the downstream areas. Chapter 6 discusses examples of both the mitigation measures and early warning systems that are already in place in Bhutan and Nepal. In addition, preliminary data from a new regular temporal monitoring system using RADAR datasets to onitor the growth of glacial lakes in Nepal is discussed.

Chapter 2

Global Climate Change and Retreat of Himalayan Glaciers in China, India, Bhutan and Nepal

The global climate system is a consequence of and a link between the atmosphere, the oceans, the ice sheets (cryosphere), living organisms (biosphere), and the soils, sediments and rocks (geosphere). Climate is normally defined as a long-term average of the weather in a certain location. Weather is the atmospheric condition at the surface of the earth and changes continuously over a timescale from minutes to weeks. However, the climate in a certain location varies between more or less extreme states and events (called the climate variability), such as severe droughts, heavy rainfall, or unusually hot or cold weather. The more extreme the events, the less frequently they occur. Recently, the occurrence of extreme weather or climatic events has been used to indicate overall climate change. Moreover, looking at the frequency of these extremes themselves is an appropriate way to predict climate change (Thomas et al 2005). Global climate change is a natural phenomenon; it is well known that the earth's average surface temperature has been increasing since the end of the Little Ice Age. The average temperature of the earth's surface did not vary much between 1940 and 1970 AD, but a continuous rise in temperature has been recorded since 1970 (Figure 2.1). Over the past few decades, human activity has significantly altered the atmospheric composition, leading to climate change of an unprecedented character (WHO/WMO/UNEP 2003). This climate change may also be reflected in the glacial environment; some measurements indicate that Himalayan glaciers have been retreating at an increased rate since 1970 (Bajracharya et al. 2006).

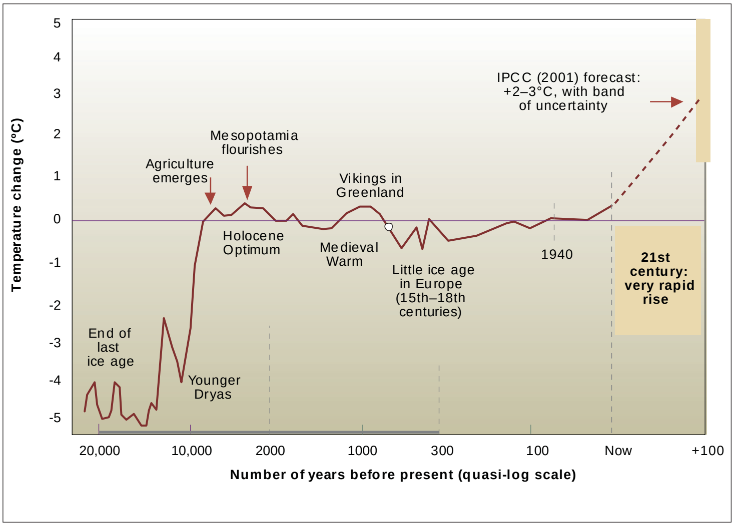


Figure 2.1: Variations in earth's average surface temperature over the past 20,000 years. From Intergovernmental Panel on Climate Change, reprinted with permission

Natural climate change

Variations in the earth's atmospheric temperature are generally governed by the amount of incoming solar radiation (terrestrial), volcanic activity (geothermal), and combustion of fossil fuel (human activity). If the earth's surface receives less solar radiation during the summer months, snow deposited during the previous winter does not all melt. When snow accumulates year after year, glaciers advance. The more albedo (shiny white surface) of snow and ice, the more solar radiation reflects back into space, causing a negative feedback to the solar thermal input cycle. Temperatures would drop even further, and eventually another ice age would occur. When the earth's surface receives more solar energy, the planet warms up due to a positive feedback mechanism; snow melts and glaciers retreat. The rise and fall in the amounts of solar energy impinging on the earth (particularly in the far north during summer) is a major driving mechanism behind climate change (Milankovitch 1920).

Human interference

The Intergovernmental Panel on Climate Change (IPCC) reported that the global atmospheric concentration of CO_2 has increased from a pre-industrial value of about 280ppm to 379 ppm in 2005. The atmospheric concentration of CO_2 in 2005 exceeded by far the natural range (180 to 300 ppm) over the last 650,000 years as determined from ice cores. The annual CO_2 concentration rate was greater during the last 10 years (1995–2005 average: 1.9 ppm per year) than it has been since the beginning of continuous atmospheric measurements (1960–2005 average: 1.4 ppm per year) although growth rates vary from year to year (IPCC 2007). Projections indicate that within the next 50 to 100 years atmospheric CO_2 concentrations will double from their pre-industrial values (Figure 2.2). The greenhouse gases trap outgoing radiation and redirect it back to the surface, causing warming. Increased concentration of greenhouse gases in the atmosphere is likely the most significant factor affecting current global climate change. Several other greenhouse gases such as methane, nitrous oxide, chlorofluorocarbons (CFCs), and tropospheric ozone are increasing in concentration because of human activities. These gases tend to reinforce the changes caused by increasing CO_2 levels. However, the observed decreases in the lower stratospheric ozone since the 1970s, caused principally by human-introduced CFCs and halogens, contribute to some cooling (IPCC 2001a).

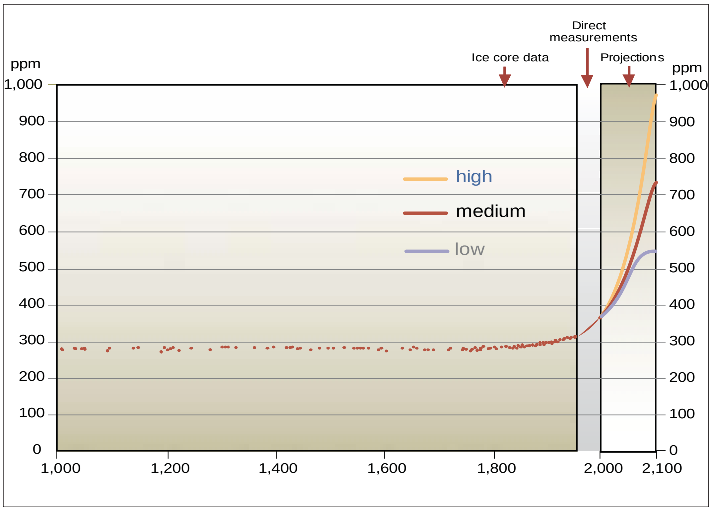


Figure 2.2: Atmospheric concentration of CO_2 from year 1000 to year 2000 (The data are from polar ice cores and from direct atmospheric measurements over the past few decades. Projections of CO_2 concentrations for the period 2000–2100 are based on the IPCC's six illustrative SRES scenarios and IS92a. From Intergovernmental Panel on Climate Change, reprinted with permission

Temperature change

Since the advent of industrialisation, human activities have contributed to a steady increase in the concentration of greenhouse gases in the atmosphere. The average surface temperature of the planet has risen between 0.3 and 0.6ºC over the past hundred years. The IPCC in its third assessment report revealed that the rate and duration of warming in the 20th century was larger than at any other time during the last thousand years. The 1990s were likely the warmest decade of the millennium in the Northern Hemisphere, and 1998 was probably the warmest year (IPCC 2001a). According to the World Meteorological Organisation (WMO), the mean global temperature in 2005 deviated by +0.47ºC from the average calculated for the period 1961–1990 (Faust 2005). However, Baker and Ekwurzel (2006) reported that measurements from 1998 and 2005 were so similar (i.e., within the error range of the different analysis methods or a few hundredths of a degree Celsius) that independent groups (e.g., NOAA, NASA and the United Kingdom Meteorological Office) calculating these rankings based on reports from the same data-collecting stations around the world disagree on which year should be ranked first. Annual global rankings are based on combined land-air surface temperature and sea surface temperatures and have been reported since 1880. Therefore, the year 2005 was pushed into a virtual tie with 1998 as the hottest year on record. For people living in the northern hemisphere – most of the world's population – 2005 was the hottest year. Similarly, 2002 and 2003 were respectively the 3rd and 4th warmest years since the monitoring and documentation of climate statistics began in 1880 (Baker et al. 2006). It is highly unusual and worrying for so many record years to occur within such a short time span.

Climate projections

According to the IPCC (2001) and its assessment based on climate models, the global temperature will continue to rise during the 21st century (Figure 2.3). The increase in the global mean temperatures over the next one hundred years could range from 1.4 to 5.8ºC (depending on the climate model used and on the intervening greenhouse gas emission scenarios). Studies show that the annual warming in the Himalayan region between 1977 and 1994 was 0.06ºC (Shrestha et al. 1999). As per the Third Assessment Report for the IPCC, the spatial average annual mean warming over the Asian region is projected to be as much as 3ºC by the 2050s and about 5ºC by the 2080s as a result of continued green house gas emissions – as calculated based on the simulation of general circulation models. However, the warming would be limited to 2.5 and 4ºC if the combined effects of greenhouse gases and

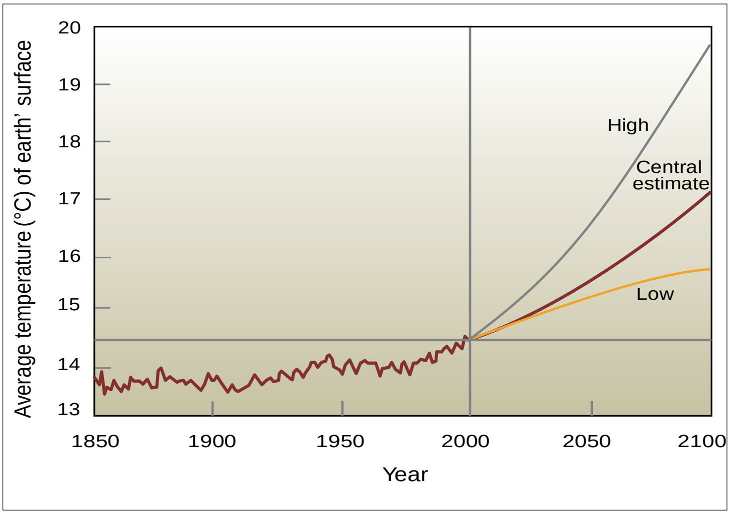


Figure 2.3: Global temperature record since instrumental recording began in 1850 and projection to 2100, according to the IPCC From Intergovernmental Panel on Climate Change, reprinted with permission

sulphate aerosols are taken into consideration. In addition, the report also warns of different warming scenarios for winter and summer in the northern hemisphere and differences in the diurnal temperature range.

On the Indian subcontinent, temperatures are predicted to rise between 3.5 and 5.5ºC by 2100. An even higher increase is predicted for the Tibetan Plateau (Lal 2002). Climate change is not just about averages, it is also about extremes. The change in climate is likely to affect both minimum and maximum-recorded temperatures as well as triggering more extreme rainfall events and storms. For the Indian sub-continent, predictions anticipate decreasing rainfall in winter and increasing precipitation during the summer monsoon. For 2050, a 10–20 per cent decrease in winter precipitation and a 30 per cent increase in summer precipitation have been projected (Lal 2002). In essence, one could expect an increase in droughts during the dry winter season and an increase in floods during the summer monsoon.

In high altitude areas of the HKH, an increased annual average temperature will cause increased thawing of permafrost and ice, including glaciers. In the short term, this may lead to an increase in annual discharge in the rivers, which carry a large proportion of the water coming from snow and ice covered areas. However, the annual discharge may eventually decrease; in particular, the dry season discharge may decline, further limiting downstream communities' access to water supply (Lal 2002).

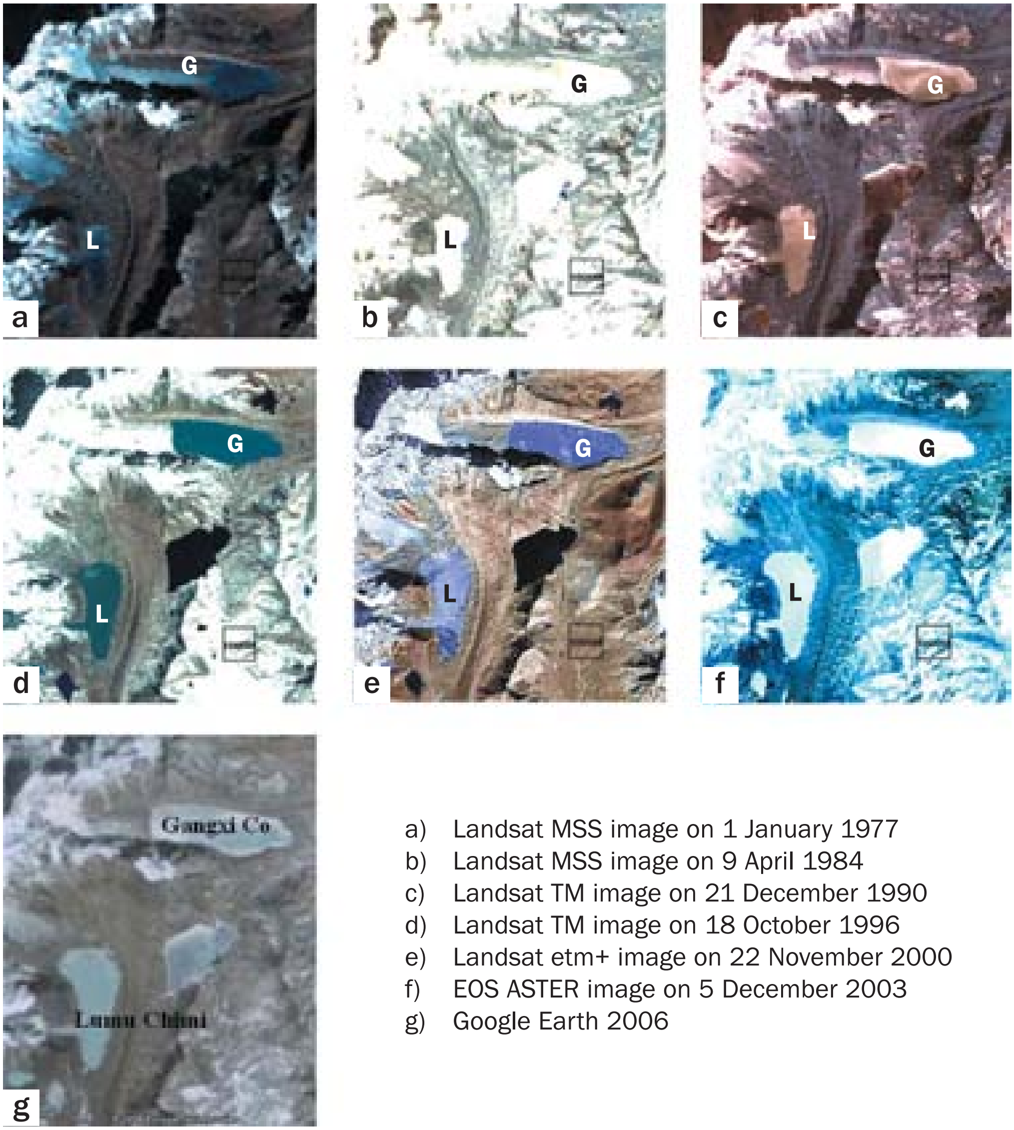
Retreat of Himalayan glaciers

Several future scenarios have been predicted for the climate of the HKH; and speculating too much about which particular scenario is more apt may be imprudent (Faust 2005). Nevertheless, it is highly likely that temperatures will increase. These changes in climate will inevitably affect glaciers and glacial lakes. The change in glacier ice or snowmelt impacts water storage and the water yield to downstream areas. Sustained glacier retreat will cause two effects on river hydrology. First, large increases in river peak flows will increase the quantity of glacio-fluvial sediments transported due to excessive melting. This can then cause large-scale damage to downstream river valley schemes such as agriculture and water supply. In addition, increasing threats arise from the formation and eventual outburst of high altitude glacial lakes. These climatic changes will have a significant impact on the lives and property of downstream communities.

Numerous studies carried out during 1999 to 2001 lend credence to the link between climate change and glacier melting. Overall, the evidence supporting the phenomenon has been conclusive enough to make glacial melting and retreat an important indicator for climate change. The Himalayan glaciers have retreated by approximately a kilometre since the Little Ice Age (Mool et al. 2001a). Studies using satellite data have tried to correlate the change in the size of existing glaciers (compared and contrasted with their previous size from historical records) with fluctuations in temperature. Results show that recession rates have increased with rising temperatures. Evidence also shows that temperature changes are more pronounced at higher altitudes. Analysis of air temperature trends across 49 stations in Nepal between 1977 and 1994, for example, reveals a clearly rising trend, and the change is much more pronounced in the higher altitude regions of the country (Shrestha et al. 1999). This has a twofold impact on the mass balance of glaciers. First, higher temperatures contribute to accelerated melting. Second, higher temperatures can cause precipitation to occur in liquid instead of solid form, even at very high altitudes. The absence of a blanketing layer of snow on the ice lowers its albedo, making glaciers further prone to radiative melting (Mool et al. 2001a).

Glaciers in China

A long-term study entitled 'The Chinese Glacier Inventory' by the Chinese Academy of Sciences has reported a 5.5 per cent shrinkage in the volume of China's 46,928 glaciers over the last 24 years, equivalent to the loss of more than 3000 sq.km of ice. Yao (2004) predicts that if the climate continues to change at the present rate, two-thirds of China's glaciers will disappear by 2050, and almost all will be gone by 2100.



a) Landsat MSS image on 1 January 1977
b) Landsat MSS image on 9 April 1984
c) Landsat TM image on 21 December 1990
d) Landsat TM image on 18 October 1996
e) Landsat etm+ image on 22 November 2000
f) EOS ASTER image on 5 December 2003
g) Google Earth 2006

Figure 2.4: Different satellite images taken between 1977 and 2006 showing the growth of Gangxi Co (G) and Lumu Chimi (L) lakes in Poiqu basin, Tibet Autonomous Region, P.R.China. See Figure 2.5 for details.

Detailed work in the Poiqu basin by Mool et al. (2005) at ICIMOD mapped 153 glaciers with a total area of 244 sq.km in 1988 and 232 sq.km in 2000, indicating an area loss of 12 sq.km (5 per cent of the total area) in 12 years. This study also noted that the valley glaciers with IDs 5O191B0029 and 5O191C0009 on the eastern slope of the Xixiabangma mountain are retreating at a rate of 45m and 68m per year respectively, and there has been about 100m shift upslope in elevation of the termini of these glaciers since 1977 (Figures 2.4 and 2.5).

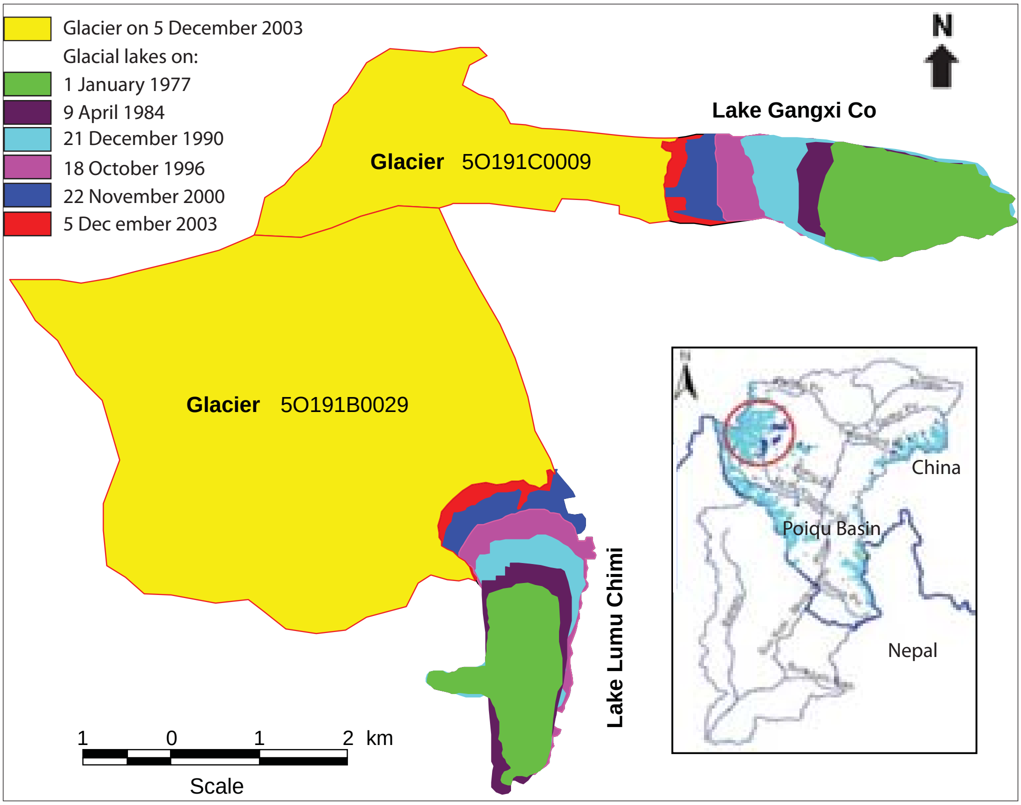


Figure 2.5: Glacier retreat and growth of Gangxi Co and Lumu Chimi lakes in Poiqu basin (from Mool et al. 2004)

Glaciers in India

Many studies have been carried out on the fluctuation of glaciers in the Indian Himalaya and significant changes (mostly retreats) have been recorded in the last three decades. The retreat of selected glaciers is summarised in Table 2.1; most of these glaciers have been retreating discontinuously since the post-glacial period (Table 2.1). For example, the Siachen and Pindari Glaciers retreated at a rate of 31.5m and 23.5m per year respectively (Vohra 1981). The Gangotri Glacier retreated by 15m per year from 1935 to 1976 and 23m per year from 1985 to 2001 (Vohra 1981; Thakur et al. 1991; Hasnain et al. 2004). On average, the Gangotri Glacier is retreating at a rate of 18m per year (Thakur et al. 1991). Jeff Kargel of the USGS showed that the position of the Gangotri Glacier snout retreated about 2 km in the period from 1780 AD to 2001 (Figure 2.6) and is continuing to retreat. Shukla and Siddiqui (1999) monitored the Milam Glacier in the Kumaon Himalaya and estimated that the ice retreated at an average rate of 9.1m per year between 1901 and 1997. Dobhal et al. (1999)

Table 2.1: **Retreat of some important glaciers in the Indian Himalaya** (modified from WWF 2005)

Glacier	Location	Period	Avg. retreat rate (m/year)	Reference
Siachen	Siachen		31.5	Vohra (1981)
Milam	Uttarakhand	1849–1957	12.5	
Pindari		1845–1966	23.5	
Gangotri		1935–1976	15	
Gangotri		1985–2001	23	Hasnain et al. (2004)
Bada Shigri	Himachal Pradesh	1890–1906	20	Mayekwski and Jeschke (1979)
Kolhani	Jammu and Kashmir	1857–1909	15	
Kolhani		1912–1961	16	
Machoi		1906–1957	8.1	Tiwari (1972) cited in WWF (2005)
Chota Shigri	Himachal Pradesh	1970–1989	7.5	Surendra et al. (1994)

Figure 2.6: Retreat of the Gangotri glacier snout during the last 220 years (from 1780 AD to 2001)

monitored the shifting of the snout of the Dokriani Bamak Glacier in the Garhwal Himalaya and found that it had retreated 586m between 1962 and 1997. The average retreat was 16.5m per year. Matny (2000) found that the Dokriani Bamak Glacier retreated by 20m in 1998, compared to an average retreat of 16.5m over the previous thirty-five years.

Table 2.2 shows the average retreat rates of other important glaciers in the Indian Himalaya. The Geological Survey of India (Vohra 1981) studied the Gara, Gor Garang, Shaune Garang and Nagpo Tokpo Glaciers of the Satluj River Basin and observed an average retreat of 4.2–6.8m per year. The Bada Shigri, Chhota Shigri, Miyar, Hamtah, Nagpo Tokpo, Triloknath and Sonapani Glaciers in the Chenab River Basin retreated at a rate of 6.8 to 29.8m per year. The highest and lowest retreat rates were reported for the Bada Shigri Glacier and Chhota Shigri Glacier respectively.

Between 1963 and 1997, Kulkarni and others found that the Janapa Glacier had retreated by 696m, the Jorya Garang by 425m, the Naradu Garang by 550m, the Bilare Bange by 90m, the Karu Garang by 800m, and the Baspa Bamak by 380m (Kulkarni et al. 2004). In their studies they observed an overall reduction of 19 per cent in glaciated area and a 23 per cent decrease in glacier volume over the last 39 years.

Based on the field survey carried out in 1999, the snout of the Shaune Garang Glacier was marked at an altitude of 4460m, whereas the Survey of India 1962 topographic map marked the snout at an altitude of 4360m (Philip and Sah 2004). This indicates a vertical shift of 100m as well as a retreat of 1500m within a span of 37 years. These authors also suggest that global warming has affected the snow-glacier melt and runoff patterns in the Himalayas. One of the best examples of glacier retreat is shown in Figure 2.6.

Table 2.2: **Average retreat rates of some major glaciers in the Indian Himalaya**

Glacier name	Retreat rate (m/year)	Reference
Gangotri	18	Thakur et al. (1991)
Milam	9.1	Shukla and Siddiqui (1999)
Dokriani Bamak	16.7 20 in 1998	Dhobal (1999) Matny (2000)
Gara,Gor Garang, Shaune Garang, Nagpo Tokpo	4.2–6.8	Geological Survey of India (Vohra 1981)
Bada Shigri, Chhota Shigri, Miyar, Hamtah, Nagpo Tokpo, Triloknath, Sonapani	6.8 for Chota Shigri 29.8 for Bada Shigri	Srivastava (2003)
Janapa	20.5	Kulkarni (2004)
Jorya Garang	12.5	
Naradu Garang	16.2	
Bilare bange	2.6	
Karu Garang	23.5	
Baspa Bamak	11.2	
Shaune Garang	40.5	Philip and Sah (2004)

Glaciers in Bhutan

Glaciers in the Bhutan Himalaya are less well studied than those in other countries. Nonetheless, there is some indication of glacier retreat in the Bhutan Himalaya. Ageta et al. (2000) examined the rate of retreat of some selected large debris-covered glaciers associated with large lakes by comparing archived photographs, satellite images, and maps of previous years. Using lake expansion rates up-valley to calculate retreat rates for the related glaciers, the authors reported retreat rates in the range of 30–35m per year. The Tarina Glacier retreat rate was 35m per year from 1967 to 1988 (Ageta et al. 2000). However, the rates were found to be variable with time, a phenomenon attributed to irregular calving at the tongue of the mother glacier, which is in contact with the lake water (Ageta et al. 2001). Debris free or 'clean' glaciers (C-type) are considered more sensitive to climate change than debris covered (D-type) ones. Karma et al. (2003) examined terminus variation for 103 debris-free glaciers in the Bhutan Himalaya over a period of 30 years (from 1963 to 1993). Retreat rates (on the horizontal projection) as high as 26.6 m/year were reported for these glaciers.

A ground survey of the C-type, Jichu Dramo glacier was conducted in the Bhutan Himalaya as part of fieldwork in 1998; the glacier was resurveyed in 1999 to assess the changes. Naito et al. (2000) recorded a 12m retreat (from 1998-1999) and estimate that the surface was lowered by 2–3m.

The retreat rates for C-type glaciers in the Bhutan Himalaya were compared with retreat rates for some glaciers in eastern Nepal. Karma et al. (2003) report that the retreat rates were higher for glaciers in the Bhutan Himalaya than for glaciers in eastern Nepal; attributing the sensitivity of these glaciers to the intensity of the monsoon. Table 2.3 shows the results.

Karma et al. (2003) studied 66 glaciers by comparing 1963 topographic maps with 1993 satellite images and found that the glaciers had retreated by 8 per cent. The glacier area from the 1963 data was 146.87 sq.km and from the 1993 data only 134.94 sq.km – a considerable decrease in 30 years. Smaller glaciers retreat at a higher rate than larger ones; some of the smaller glaciers (<0.2 sq.km area) seen in 1963 had completely disappeared by 1993.

Table 2.3: **Average variation rates of glacier termini in east Nepal and Bhutan in recent decades (adapted from Karma et al. 2003)**

Region	Period (years)	Variation rate (m/year)		No. of glaciers
		Vertical	Horizontal	
For all types (retreating, stationary, and advancing glaciers)				
Nepal	33 (1959–1992)	0.59	3.14	100
Bhutan	30 (1963–1993)	1.90	6.27	103
For retreating and stationary glaciers only				
Nepal	33 (1959–1992)	1.13	4.36	88
Bhutan	30 (1963–1993)	1.90	6.27	103
For retreating glaciers only				
Nepal	33 (1959–1992)	1.72	6.61	58
Bhutan	30 (1963–1993)	2.23	7.36	86

Glacier retreat in the Pho Chu sub-basin of Bhutan

The study of glaciers and glacial lakes in the Lunana basin from 1968 to 1998 showed retreating glaciers and growing glacial lakes (Figures 2.7, 2.8 and 2.9) (Mool et al. 2001). The Luggye Glacier retreated by 160m per year from 1988 to 1993, resulting in a high growth rate of Lake Luggye Tso. The Raphsthreng Glacier retreated on average 35m per year from 1984 to 1998, but from 1988 to 1993 the retreat rate was 60m per year. It is noteworthy that, for all the years studied, the decadal growth of glacial lakes has been rapid for all lakes, except for the lake associated with the Drukchung Glacier. Glacial lakes are discussed in detail in the following chapter.

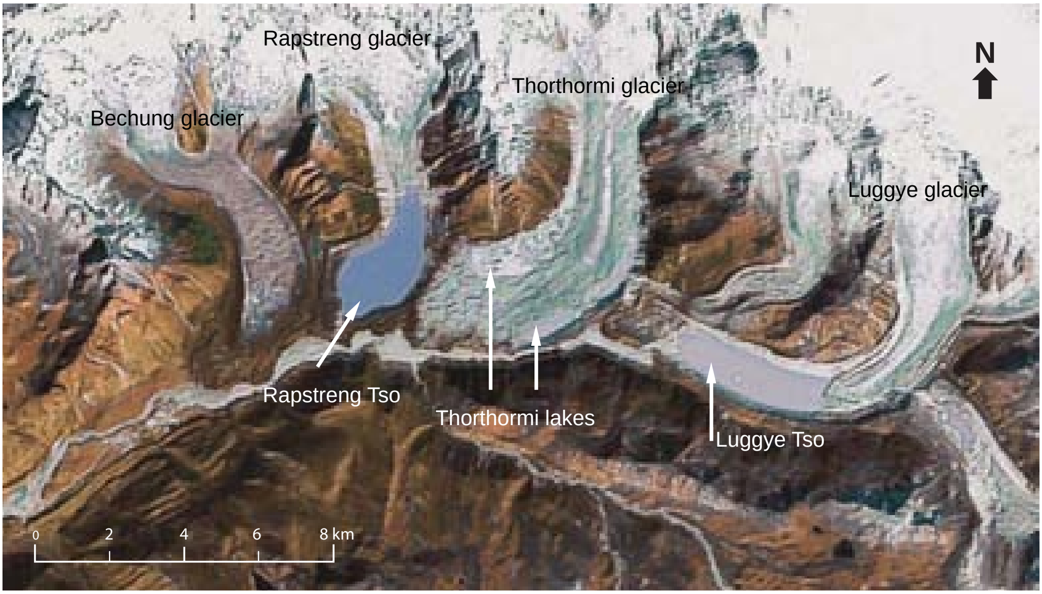


Figure 2.7: Glaciers and glacial lakes in the Lunana basin, base image Google Earth

Glaciers in Nepal

ICIMOD undertook the first ever attempt to carry out a systematic study of glaciers and glacial lakes throughout Nepal in 2001 and that study provided the first baseline information. Previously, no systematic study of glacial activity had been made in Nepal and most studies were sporadic investigations of individual small mountain basin glaciers and some valley glaciers. For example, different scholars had studied the glaciers of the Kanchenjunga, Khumbu, Langtang, and Dhaulagiri regions since the 1970s in an attempt to understand glacial activity. A major finding of the ICIMOD work is that glaciers in Nepal retreated dramatically between 1994 and 1998. Asahi et al. (2001) of the Glaciological Expedition in Nepal (GEN 2006) and Kadota et al. (1997) measured glacier retreat in the Khumbu and Shorang regions and positioned benchmarks in the vicinity of the termini of 19 small debris-free glaciers. They found that glaciers in the Shorang region retreated an average of 8m per year; and glaciers in the Khumbu region retreated an average of 5 to 10m per year. They also remarked that the glacier retreat rate accelerated after 1990 (Figure 2.10a and Table 2.4).
During the 30-year period from 1970 to 2000, the loss of glacier area in the Tamor River sub-basin of Nepal (Bajracharya et al. 2006b) was about 5.9 per cent or 0.2 per cent per year. Fujita et al. (2001) reported a higher glacier retreat rate between the 1970s and the 1990s

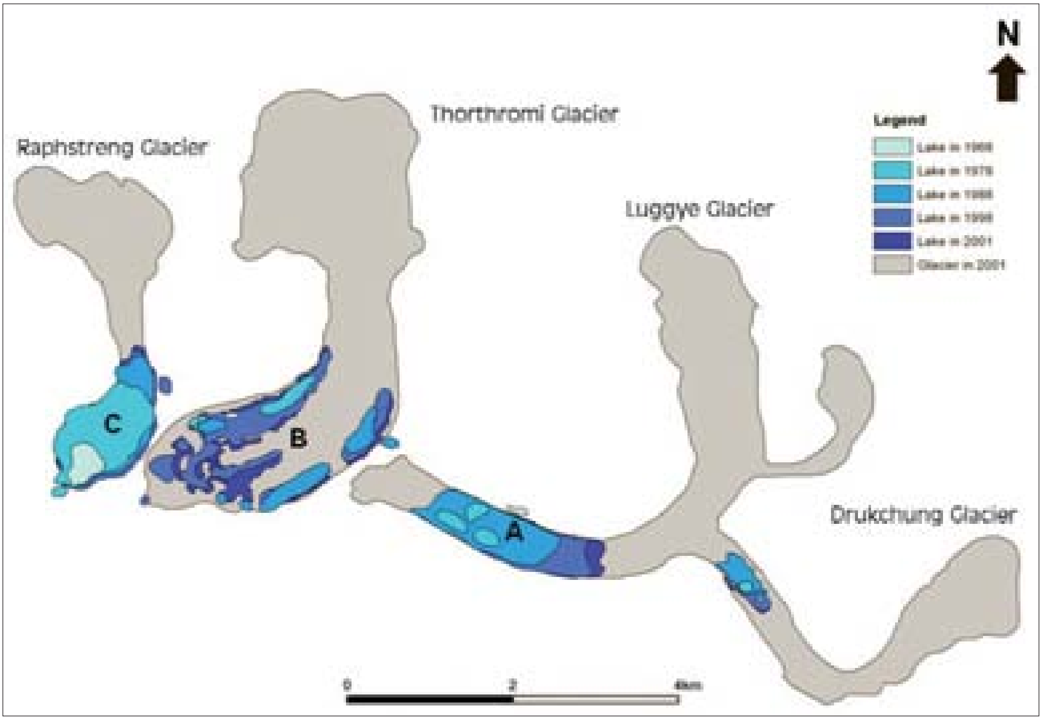


Figure 2.8: Glacier retreat and growth of glacial lakes in the Lunana basin

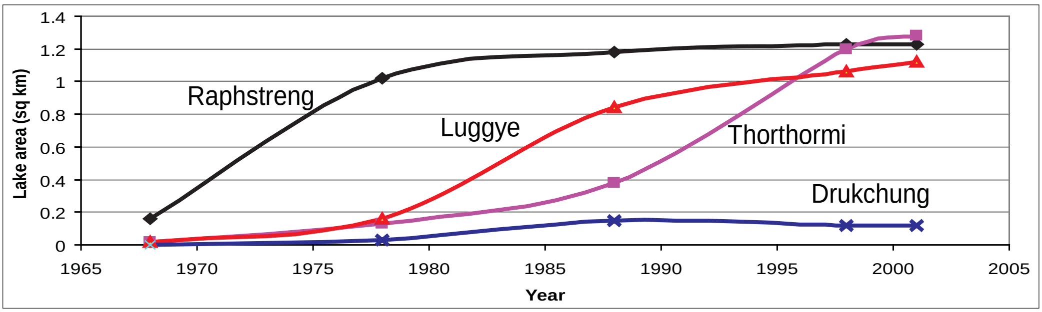


Figure 2.9: Development trend of glacial lakes in the Lunana basin

Table 2.4: **Retreat rates of some glaciers in the Nepal Himalaya**

Glacier name	Retreat rate	Reference
AX010	30 m per year (1978–1989)	Fujita (2001)
Khumbu	10 m surface lowering from 1978 to 1995	Kadota et al. (2000)
Seven unnamed clean type glaciers in Khumbu region	30–60 m per year (1970s to 1989)	Yamada et al. (1992)
Imja glaciers	41m per year (1962 to 2001) and **74** m per year (2001 to 2006)	Bajracharya (2006a)
Trakarding glacier	66 m per year (1957 to 2000)	WECS (1993), Bajracharya (2005)

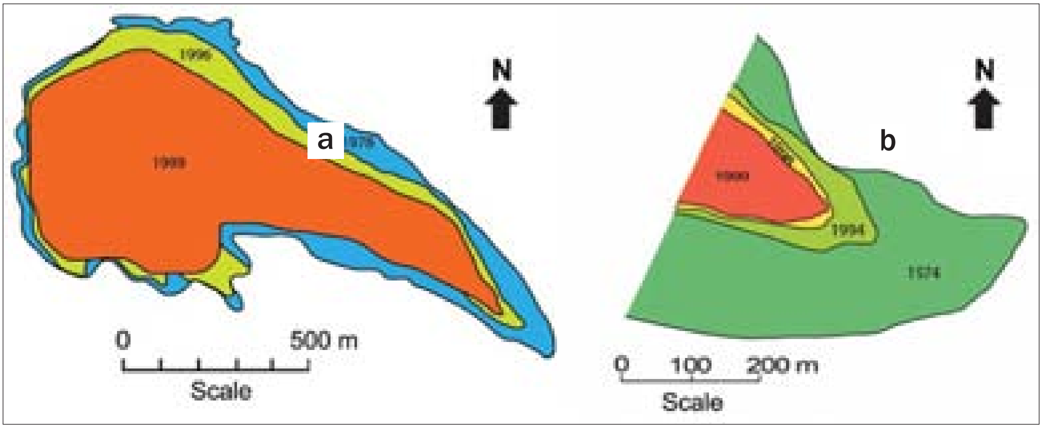


Figure 2.10: Maps depicting the changes in glacier area on different dates: a) AX010 glacier, Shorang Himal; b) Rika Samba glacier, Dhaulagiri region (Adapted from Fujita et al. 2001)

in the Shorang Himal area of eastern Nepal as well as in the Rika Samba glacier of the Dhaulagiri region of western Nepal (Fujita et al. 2001; Figure 2.10).

Glacier retreat in the Dudh Koshi sub-basin

The Dudh Koshi sub-basin is one of the largest glaciated basins in Nepal. To understand the activity of glaciers in this region between 1960 and 2001, some of the valley glaciers' tongues were delineated in satellite images and compared (1976 Landsat MSS and 1992 Landsat TM and Landsat etm+ (Nature Vue) of 2001). The Dudh Koshi sub-basin is home to about 36 valley glaciers; of these, due to certain limitations of the remote sensing (such as shadows, poor resolution, etc.), only 24 have been studied by satellite imaging in 1976, 1992, and 2000/2001 to identify their retreat rate. All of the valley glaciers in the Dudh Koshi sub-basin that could be studied had retreated by at least 10 to 59m per year. The glaciers show a remarkable change from the 1960s to 2001. In general, glaciers are shrinking and valley glaciers are retreating. The consequence of this is that an increasing number of moraine-dammed lakes are forming. The minimum retreat of glaciers was not less than 400m and the maximum was 2340m in 40 years (Table 2.5). The average minimum glacier retreat rate was 10m per year; this was observed on the Langdak, W. Lhotse, Lhotse, and Setta glaciers. **The fastest retreating glacier was the Imja glacier, with an average rate of 59m per year and a surprising 74m per year for the past half decade**. Other fast-retreating glaciers are W. Chamjang and Ombigaichain.

A good indicator of glacier retreat is the growth of supraglacial lakes; these are discussed at length in the following chapter. The noted continuous retreat of glaciers highlights the importance of monitoring. It will be important to continue monitoring the Himalayan glaciers and glacial lakes for the sound management of water resources. However, the study of this phenomenon will also continue to remain a challenge; the limits imposed by the higher altitude, the rarefied atmosphere, the remoteness of many of the locations and the short mapping season cannot be underestimated.

Table 2.5: **Retreat rates of some valley glaciers in the Dudh Koshi sub-basin, Nepal**

S.N.	Glacier ID	Glacier Name	Mean length (m) in year		Total retreat (m) within period			Average retreat rate (m/year) between 1960–2001
			1960s	2000 or 2001	1960–2001	1976–2001	1992–2001	
1.	Kdugr 21	Lumding	6,015	4,700	1,315	1,015	184	33
2.	Kdugr 40	Langmuche	3,160	2,388	772	323	323	19
3.	Kdugr 47	Langdak	4,430	4,028	402	209	209	10
4.	Kdugr 48	Chhule	7,600	6,818	782	534	534	20
5.	Kdugr 52	Melung	8,870	7,430	1,440	375	0	36
6.	Kdugr 54	Bhote Koshi	17,100	16,455	645	400	330	16
7.	Kdugr 67	Lumsamba	9,500	8,955	545	466	242	14
8.	Kdugr 100	Ngojumba	22,500	21,625	875	350	300	22
9.	Kdugr 120	Cholo	2,520	1,586	934	753	170	23
10.	Kdugr 133	Khumbu	12,040	11,198	842	483	145	21
11.	Kdugr 152	Nuptse	6,330	5,898	432	309	124	11
12.	Kdugr 153	W.Lhotse	4,110	3,722	388	186	116	10
13.	Kdugr 156	Lhotse	8,870	8,453	417	280	173	10
14.	Kdugr 160	Imja	10,770	8,430	2,340	812	558	59
15.	Kdugr 166	Ombigaichain	4,110	2,123	1,987	1,205	994	50
16.	Kdugr 167	?	5,060	4,311	749	640	600	19
17.	Kdugr 169	Amadabalam	2,530	2,056	474	390	301	12
18.	Kdugr 170	Setta	2,215	1,811	404	276	255	10
19.	Kdugr 186	Kyashar	6,330	5,797	533	?Shadow	245	13
20.	Kdugr 202	Sabai (Sha)	4,110	3,511	599	0	0	15
21.	Kdugr 205	Inkhu	10,770	9,786	984	824	561	25
22.	Kdugr 221	?	3,160	2,683	477	?Shadow	367	12
23.	Kdugr 233	?	1,900	1,259	641	330	228	16
24.	Kdugr 264	W.Chamjang	3,800	1,558	2,242	1,015	550	56

Case Studies from Nepal and Bhutan

Chapter 3

Glacial Lakes in the Dudh Koshi Sub-basin of Nepal and Pho Chu Sub-basin of Bhutan

Glacial lakes are formed when the glacier ice melts. Most present-day large glacial lakes are end-moraine lakes that have grown from small supraglacial lakes. Some of the lakes that have been studied in detail from the beginning of the lake formation show that the rate of lake extension is directly proportional to glacier retreat.

A study carried out by ICIMOD (1999–2001) identified the glacial lakes larger than 0.003 sq.km situated above an altitude of 3500m and reported 2323 lakes in Nepal and 2674 lakes in Bhutan (Mool et al. 2001a, b). These data were based mainly on topographic maps from the early 1960s. Over the past 40 years, the glaciers have been retreating with a resulting increase in the size of associated glacial lakes. Each lake larger than 0.02 sq.km contains at least $6x10^5$ m^3 of water; if it breaches, downstream valleys could suffer hazardous consequences. Therefore, these are defined hereafter as 'major' glacial lakes. Monitoring these lakes, both by remote sensing and field verification, is the important groundwork needed for planning and implementing mitigative measures and installing early warning systems. Case studies of glacial lakes in the Dudh Koshi sub-basin of Nepal and Pho Chu sub-basin of Bhutan are presented below.

Glacial lakes of the Dudh Koshi sub-basin of Nepal

The Dudh Koshi sub-basin is the largest basin in Nepal. In terms of glacial lakes, it is perhaps the most densely glaciated region of the country (Bajracharya et al. 2004; Figure 3.1). Mool et al. (2001a) mapped 473 glacial lakes in this region using archival data from the 1960s, but by 2006 only 296 could be re-identified using NaturalVue images from EarthSat (Table 3.1). Of the 177 lakes that disappeared most were erosion lakes, the remainder being either supraglacial lakes or moraine-dammed lakes.

Over time, erosion lakes dry up, and supraglacial lakes are transformed into moraine-dammed ones. Their number has decreased drastically (by approximately 37 per cent), while the lakes associated with glaciers have increased in size by 21 per cent (Table 3.1). Most of the supraglacial lakes have either disappeared or been transformed into moraine-dammed lakes. The increased percentage in surface area is due to the proliferation of moraine-dammed lakes. In addition, 34 major glacial lakes are growing and 24 new major lakes have appeared (Table 3.2). Among these newly formed lakes are 15 moraine-dammed lakes, five supraglacial lakes, two valley lakes and two erosion lakes (Table 3.3). The areas of the major glacial lakes range from 0.021 sq.km to 0.848 sq.km, at altitudes of between 4,349 and 5,636m.

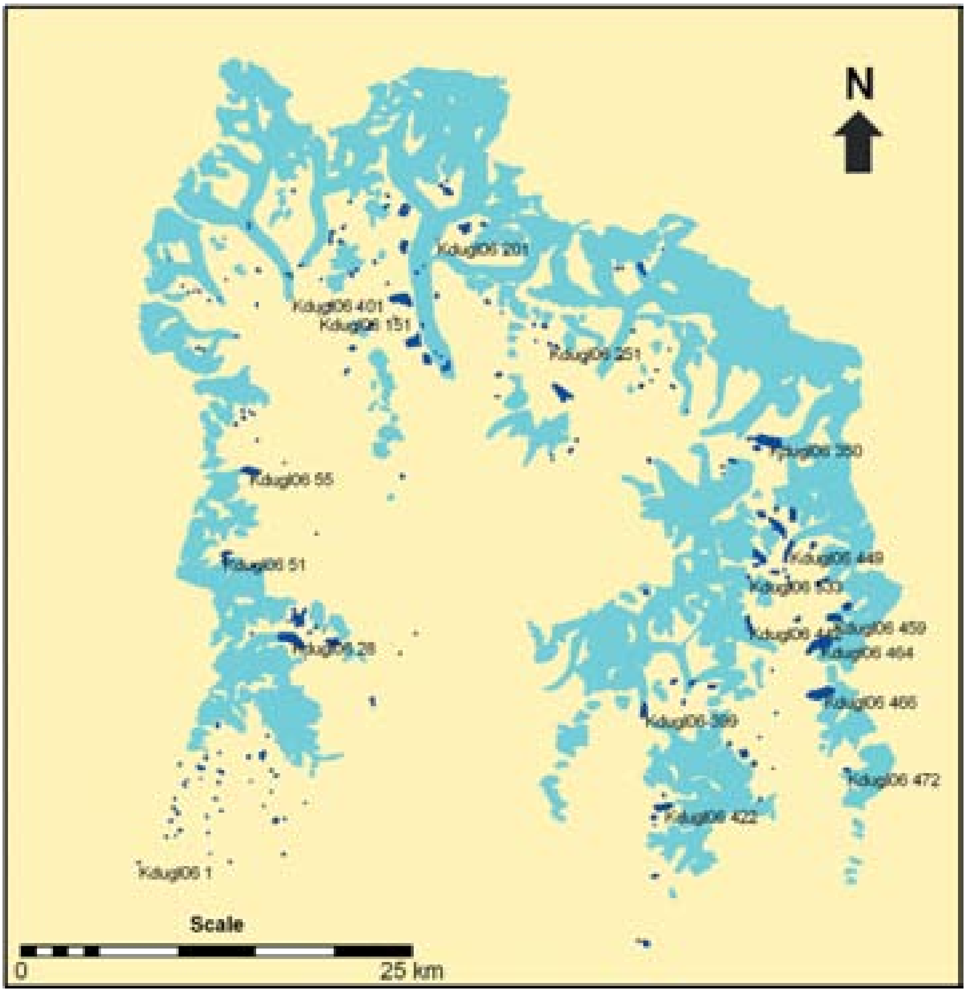


Figure 3.1: Glacial lakes in the Dudh Koshi sub-basin in 2001
(Note: the numbering of lakes starts from the outlet of the major stream and proceeds clockwise round the basin.)

Table 3.1: **Glacial lakes in the Dudh Koshi sub-basin (1960s and 2000)**

Type of lake	Number			Area ('000 m^2)			Area of largest lake ('000 m^2)
	1960s	2000	% change in number	1960s	2000	% change	
Supraglacial (S)	267	72	-73	3,369	1,286	-62	121
Erosion (E)	141	98	-30	3,607	2,218	-39	356
Moraine-dammed (M)	33	89	170	2,291	7,254	217	848
Valley (V)	13	16	23	1,706	2,709	59	836
Blocked (B)	10	17	70	1,764	2,146	22	554
Cirque (C)	9	4	-56	335	226	-32	147
Total	473	296	-37	13,074	15,843	21	

Note: the conventional signs in the above table represent negative (-) for decrease in area and positive for increase in area.

B = main glacier blocking the branch valley; C = rounded, steep-walled in three sides;
E = formed at paleo-glacier area; M = dammed by end moraine; S = within glacier; V = along river valley

The Dudh Koshi basin has experienced a number of GLOF events in recent times: the Nare GLOF in 1977, the Dig Tsho GLOF in 1985, and the Tam Pokhari GLOF in 1998. A GLOF from Lake Kdu_gl 458/459 (associated with glacier Kdu_gr 260) was also inferred from satellite imagery of 2001. These GLOF events have caused extensive damage to roads, bridges, trekking trails, and villages, as well as loss of human life and other infrastructure (Fushimi et al. 1985; Galey 1985; Ives 1986; Vuichard and Zimmerman 1987). Despite numerous glacial lakes and past outburst floods, the basin still contains many potentially dangerous glacial lakes. In all likelihood, this basin will experience another GLOF event in the near future. While the basin is very remote and is located at an extreme elevation, as one of the most popular trekking routes in the Everest region it is nevertheless highly populated. Precisely because of the population density, it was singled out for potential GLOF hazard and risk assessment, and for hydrodynamic modelling.

Table 3.2: **Summary of activity of glacial lakes in the Dudh Koshi sub-basin (1960 –2000)**

Disappeared (or less than 50×50 sq. m) lakes	**245**
Supraglacial lakes	199
Erosion lakes	34
Valley lakes	3
End moraine-dammed lakes	2
Lateral moraine dammed lakes	5
Cirque	2
Converted lakes (from supraglacial to end moraine-dammed)	**11**
New lakes	**24**
Supraglacial lakes	5
Erosion lakes	2
Valley lakes	2
End moraine-dammed lakes	15
Growing lakes	**34**
Supraglacial lakes	10
Valley lakes	2
End or lateral moraine-dammed lakes	17
Blocked lakes	2
Erosion lakes	3

Potentially dangerous glacial lakes in the Dudh Koshi sub-basin of Nepal

The Dudh Koshi basin contains twelve potentially dangerous glacial lakes, the largest number in any sub-basin of Nepal studied so far. All 12 potentially dangerous glacial lakes are moraine dammed lakes. The most well known lakes in this sub-basin are Lumding Tsho, Dig Tsho, Chokarma Cho, Imja Tsho, Tam Pokhari, Dudh Pokhari, Hungu, and Chamjang (Table 3.4). The Dig Tsho and Tam Pokhari lakes have experienced outburst events in the recent past. Field data indicate that Lake Dig Tsho is no longer dangerous and should be removed from the inventory. Three lakes: Kdu_gl 422, 442 and 462 have remained more or less the same size; a satellite image of 2001 showed that Lake Kdu_gl 444 no longer exists. In summary, of the twelve potentially dangerous glacial lakes listed in the Dudh Koshi sub-basin, two can be removed from the 'dangerous' list and four are more or less constant in size. The remaining six (Kdu_gl 28, 350, 449, 459, 464 and 466) are growing and expected to eventually breach.

Detailed studies of Lakes Dig Tsho and Imja Tsho

Lake Dig Tsho was at one time a 'potentially dangerous' glacial lake and did suffer a GLOF event in 1985. Lake Imja Tsho is a similar but much larger and rapidly growing lake in the same area. These two lakes share much of the same downstream terrain. The similarity between them means that information gathered from Lake Dig Tsho can be used to model and possibly predict how events may unfold at Lake Imja Tsho. These two lakes are discussed below in detail.

Table 3.3: **Activity of glacial lakes in association with glaciers in the Dudh Koshi sub-basin (1960s-2000)**

S.N.	Lake		Type	Area (sq m) in		Associated glacier number	Distance to glacier (m)
	Number	Name/ Latitude, longitude		2000	1960s		
1.	Kdu_gl 28	Lumding Tsho	M dammed	836,765	104,944	Kdu_gr 21	0
2.	Kdu_gl 40		M dammed	23,289	18,914	Kdu_gr 24	270
3.	Kdu_gl 41		M dammed	74,197	26,289	Kdu_gr 25	785
4.	Kdu_gl 43		M dammed	25,888	13,662	Kdu_gr 26	70
5.	Kdu_gl 47		Blocked	35,593	12,866	Kdu_gr 32	45
6.	Kdu_gl 52		M dammed	30,921	2,096	Kdu_gr 35	785
7.	Kdu_gl 55	Dig Tsho*	M dammed	375,681	143,250	Kdu_gr 40	0
8.	Kdu_gl 69		Supraglacial	23,322	3,316	Kdu_gr 48	0
9.	Kdu_gl 71		Supraglacial	21,194	4,404	Kdu_gr 49	300
10.	Kdu_gl 150		Erosion	25,489	16,394	x	x
11.	Kdu_gl 158	Tanjung Tsho	Valley	218,681	169,539	x	x
12.	Kdu_gl 160		Erosion	27,473	15,439	Kdu_gr 87	670
13.	Kdu_gl 163		M dammed	21,905	3,714	x	x
14.	Kdu_gl 168	Ngojumba Tsho	Valley	220,465	143,940	x	x
15.	Kdu_gl 177		Supraglacial	28,412	4,138	Kdu_gr 100	0
16.	Kdu_gl 222		Supraglacial	24,289	15,147	Kdu_gr 100	0
17.	Kdu_gl 229		Erosion	20,184	17,933	Kdu_gr 113	515
18.	Kdu_gl 255		Supraglacial	48,496	10,425	Kdu gr 130	0
19.	Kdu_gl 286		Supraglacial	22,191	6,765	Kdu_gr 133	0
20.	Kdu_gl 287		Supraglacial	121,762	48,811	Kdu_gr 133	0
21.	Kdu_gl 300	Paugungagayang	Block/valley	23,474	16,606	Kdu_gr 133	95
22.	Kdu_gl 340		Supraglacial	23,220	9,391	Kdu_gr 156	0
23.	Kdu_gl 342		Supraglacial	41,503	6,977	Kdu_gr 156	0
24.	Kdu_gl 350	Imja Tsho	M dammed	848,742	48,811	Kdu_gr 160	0
25.	Kdu_gl 384		M dammed	29,750	14,431	Kdu_gr 169	245
26.	Kdu_gl 387		Supraglacial	23,706	4,085	Kdu_gr 284	0
27.	Kdu_gl 399	Tam Pokhari*	M dammed	265,386	138,846	Kdu_gr 202	0
28.	Kdu_gl 442		M dammed	194,966	133,753	Kdu_gr 247	845
29.	Kdu_gl 446		M dammed	349,263	207,314	Kdu_gr 289	0
30.	Kdu_gl 449		M dammed	232,842	198,905	Kdu_gr 249	0
31.	Kdu_gl 459		M dammed	296,886	78,761	Kdu_gr 260	80
32.	Kdu_gl 464		M dammed	783,553	349,397	Kdu_gr 262	0
33.	Kdu_gl 466		M dammed	831,427	6,446	Kdu_gr 264	0
34.	Kdu_gl 472		M dammed	46,215	6,526	Kdu_gr 293	0
35.	Kdu_gl 483	27°43'39"N, 86°34'22"E	M dammed	34,016	New	Kdu_gr 3	0
36.	Kdu_gl 488	27°44'31"N, 86°40'24"E	Erosion	26,686	New	x	x
37.	Kdu_gl 489	27°44'42"N, 86°40'21"E	Erosion	34,246	New	x	x
38.	Kdu_gl 491	27°46'39"N, 86°38'44"E	M dammed	286,119	New	Kdu_gr 28	245
39.	Kdu_gl 495	27°54'32"N, 86°35'00"E	M dammed	20,044	New	Kdu_gr 46	405
40.	Kdu_gl 501	27°57'30"N, 86°39'50"E	M dammed	60,039	New	Kdu_gr 87	270
41.	Kdu_gl 502	27°59'20"N, 86°39'06"E	M dammed	58,097	New	Kdu_gr 90	0
42.	Kdu_gl 504	27°52'24"N, 86°41'17"E	Valley	32,090	New	x	x
43.	Kdu_gl 505	27°56'10"N, 86°42'48"E	Supraglacial	48,184	New	Kdu_gr 100	0
44.	Kdu_gl 511	27°59'27"N, 86°41'38"E	Supraglacial	27,858	New	Kdu_gr 100	0
45.	Kdu_gl 513	28°02'30"N, 86°42'31"E	M dammed	38,349	New	Kdu_gr 100	210
46.	Kdu_gl 517	27°48'38"N, 86°50'52"E	M dammed	69,238	New	Kdu_gr 208	0
47.	Kdu_gl 520	27°54'01"N, 86°54'45"E	M dammed	28,950	New	x	x
48.	Kdu_gl 521	27°53'13"N, 86°54'01"E	M dammed	65,368	New	Kdu_gr 282	0
49.	Kdu_gl 522	27°53'00"N, 86°53'43"E	M dammed	22,274	New	Kdu_gr 166	135
50.	Kdu_gl 524	27°42'49"N, 86°55'12"E	M dammed	67,607	New	Kdu_gr 240	310
51.	Kdu_gl 526	27°43'28"N, 86°54'13"E	M dammed	31,381	New	Kdu_gr 240	170
52.	Kdu_gl 528	27°49'26"N, 86°55'54"E	M dammed	46,225	New	Kdu_gr 287	880
53.	Kdu_gl 529	27°49'02"N, 86°56'26"E	Valley	31,838	New	x	x
54.	Kdu_gl 532	27°49'51"N, 86°56'14"E	M dammed	28,520	New	x	x
55.	Kdu_gl 533	27°49'15"N, 86°54'50"E	M dammed	25,197	New	Kdu_gr 288	95
56.	Kdu_gl 536	27°58'08"N, 86°42'05"E	Supraglacial	27,084	New	Kdu_gr 100	0
57.	Kdu_gl 539	27°55'20"N, 86°55'05"E	Supraglacial	34,459	New	Kdu_gr 156	0
58.	Kdu_gl 543	27°45'57"N, 86°52'31"E	Supraglacial	21,467	New	Kdu_gr 205	0

* Dig Tsho GLOF of 1985, Tam Pokhari GLOF of 1998, M: moraine, x: no data

Table 3.4: **Potentially dangerous glacial lakes in the Dudh Koshi sub-basin**									
Lake ID	**Name**	**Latitude (N)**	**Longi-tude (E)**	**Alti-tude (m)**	**Length (m)**		**Area (sq m)****		**Remark**
					1960s	**2000**	**1960s**	**2000/01**	
Kdu_gl 28 (D)	Lumding Tsho	27° 46.51'	86° 37.53'	4,846	625	1952	104,944	836,765	Growing
Kdu_gl 350 (E)	Imja Tsho	27° 54.00'	86° 55.40'	5,023	410	1822	48,811	848,742	Rapid growth
Kdu_gl 399 (F)	Tam Pokhari	27° 44.33'	86° 50.76'	4,431	515	925	138,846	265,386	GLOF on 3 September 1998
Kdu_gl 422 (G)	Dudh Pokhari	27° 41.21'	86° 51.68'	4,760	1,120	1095	274,297	297,574	No change in area
Kdu_gl 442 (H)	Unnamed	27° 47.70'	86° 54.81'	5,266	840	1082	133,753	194,966	No change in area
Kdu_gl 444 (I)	Unnamed	27° 48.23'	86° 56.61'	5,056	420	–	112,398	–	Dried/breached
Kdu_gl 449 (J)	Hungu	27° 50.17'	86° 56.26'	5,181	875	1054	198,905	232,842	Merged with gl 532
Kdu_gl 459 (K)	East Hungu 1	27° 47.92'	86° 57.95'	5,379	465	1055	78,761	296,886	Possibly merged with 458 and 460
Kdu_gl 462 (L)	East Hungu 2	27° 48.30'	86° 58.65'	5,483	640	448	211,877	178,317	No change in area
Kdu_gl 464 (M)	Unnamed	27° 46.86'	86° 57.22'	5,205	1,100	1918	349,397	783,553	Growing
Kdu_gl 466 (N)	West Chamjang	27° 45.24'	86° 57.33'	4,983	125	1699	6,446	831,427	Kdu-gl 465 to 469 merged into one
Kdu_gl 55 (O)*	Dig Tsho	27° 52.41'	86° 36.61'	4,364	605	1262	143,250	375,681	GLOF on 4 August 1985, no danger

* Based on field verification, Dig Tsho can be removed from the list of potentially dangerous lakes.
** Due to different map projections and sources used, the area of a lake may differ slightly.

Lake Dig Tsho

Dig Tsho glacial lake is located in the Langmoche Valley sub-basin of the Nangpo-Tsangpo area in the Bhote Koshi valley at 27° 52’ 25”N latitude and 86° 35’ 37”E longitude. Lake Dig Tsho is referenced as Kdu_gl 55. The lake is located at an altitude of 4,365m, and is fed by the steep Langmoche glacier (Figure 3.2). The Langmoche Glacier is a clean type glacier (referenced as Kdu_gr 40) that originates at 5,400m at the foot of the northeast face of Tangri Ragi Tau (6,940m) and is extensively nourished by snow avalanches. The glacier snout is exposed to heavy solar radiation, which has contributed to its rapid retreat and to the thinning of the snout in recent decades.

The lake is believed to have been full to its rim just before the outbreak on 4 August 1985. The centre of the lake was estimated to have been 20m deep (WECS 1987). The lake was dammed by a 60m high moraine assumed to have been formed during the Little Ice Age; the estimated composition of the moraine consisted of boulders (20 per cent), cobbles (25 per cent), gravel (40 per cent), sand and silt (15 per cent). The river valley and lake outlet consist mainly of boulders and cobbles (Figure 3.3).

Before its outbreak, Lake Dig Tsho had been impounded between well-developed end moraines and the receding Langmoche terminus. According to Vuichard and Zimmerman (1987), the maximum extent that the lake attained before the outbreak was 0.5 sq.km. The development of Lake Dig Tsho is analysed based on time series satellite images (Table 3.5 and Figures 3.4 and 3.5). The crescent shaped lake (of about 0.2 sq.km in size) already existed in the Corona image of December 1962. The lake had grown to 0.33 sq.km in 1975, and attained a maximum area of about 0.6 sq.km in 1983. This area is about 0.1 sq.km larger than suggested by Vuichard and Zimmerman (1987). The Landsat image of 1989, four years after the outburst, shows an area for Lake Dig Tsho of 0.3 sq.km — more or less the

Figure 3.2: Lake Dig Tsho in the foreground and Langmoche Glacier in the background (10 Oct 2006)

Figure 3.3: Outlet of Lake Dig Tsho after 1985 GLOF (10 Oct 2006)

Table 3.5: **Development of Lake Dig Tsho from 1962 to 2005**

Fig	Year	Area (sq m)	Diff in area	Length (m)	Diff in length	
a.	1962	201,172		402		
b.	1975	334,861	133,689	669	267	0.32 km
c.	1983	597,923	263,062	1195	526	
d.	1989	315,865	-282,058	631	-564	
e.	1992	376,575	60,710	753	121	Outburst in 1985
f.	2000	361,867	-14,708	723	-29	
g.	2005	330,000		877		1.21 km

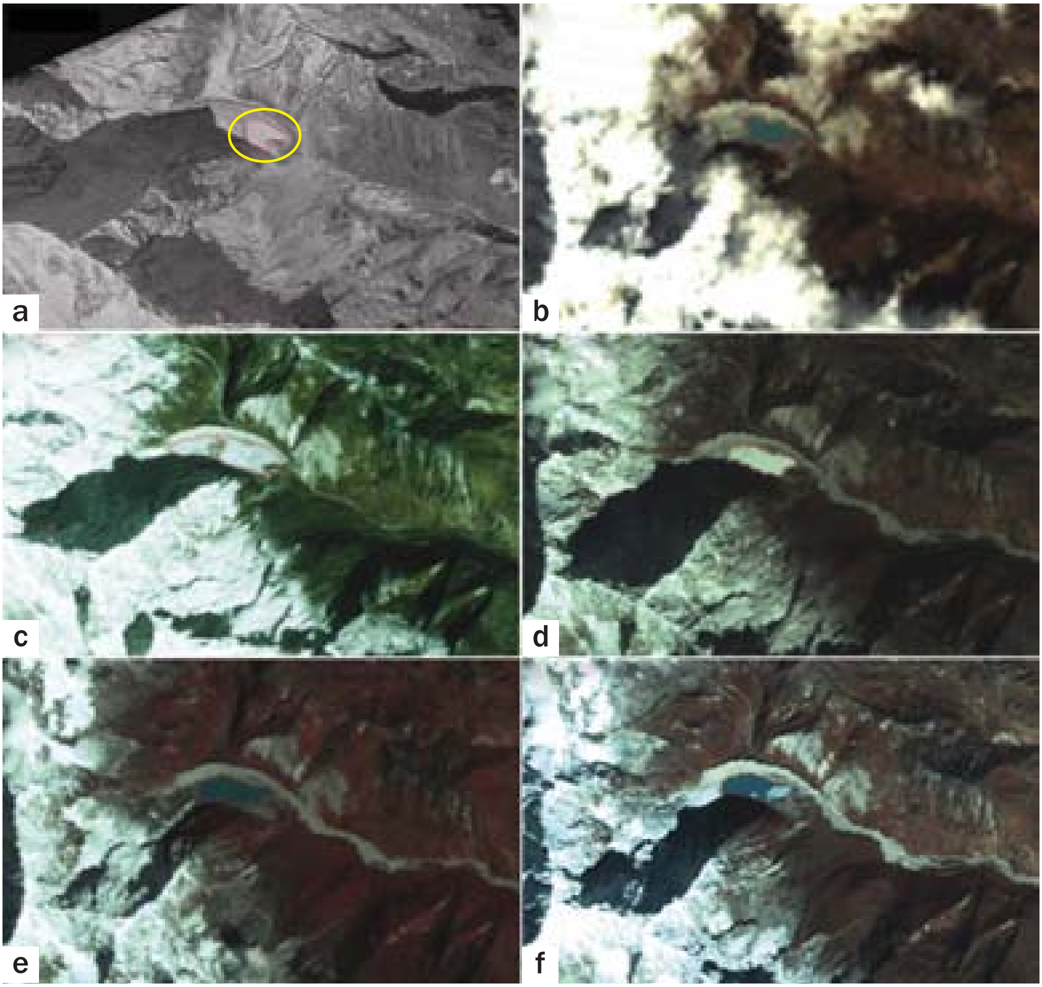


Figure 3.4: Lake Dig Tsho (D) in different satellite images taken between 1962 and 2000. Debris along the valley can be seen in the satellite images after 1985: a) Corona, 15 December 1962, b) Landsat MSS, 15 October 1975, c) Space Shuttle, 02 December 1983, d) Landsat5 TM, 11 December 1989, e) Landsat5 TM, 22 September 1992, f) Landsat7 etm+, 30 October, 2000

same as the 0.35 sq.km area reported in satellite images of 1992 and 2000, indicating stabilisation of the lake. The outer slope of the moraine dam is covered by vegetation while the inner slope is bare and unstable, a characteristic common to moraine dams. The stream draining out of Lake Dig Tsho is called Langmoche Khola, and is a tributary of the Bhote Koshi.

Dig Tsho GLOF of 1985

The Dig Tsho GLOF occurred on 4 August 1985 in the Dudh Koshi sub-basin. The event was triggered by an ice avalanche from the Langmoche glacier which induced a dynamic wave on the lake. Vuichard and Zimmerman (1987) reported that an ice mass of 100 to 200 thousand m^3 dislodged itself from the overhanging glacier tongue and plunged into the lake. According to this report, the flood began in the early afternoon and lasted for 4–6 hours. By reconstructing the hydrograph they estimated that the peak flood had been 1600 m^3s^{-1}, but Cenderelli and Wohl (2001) estimated a much higher peak discharge of 2350 m^3s^{-1}.

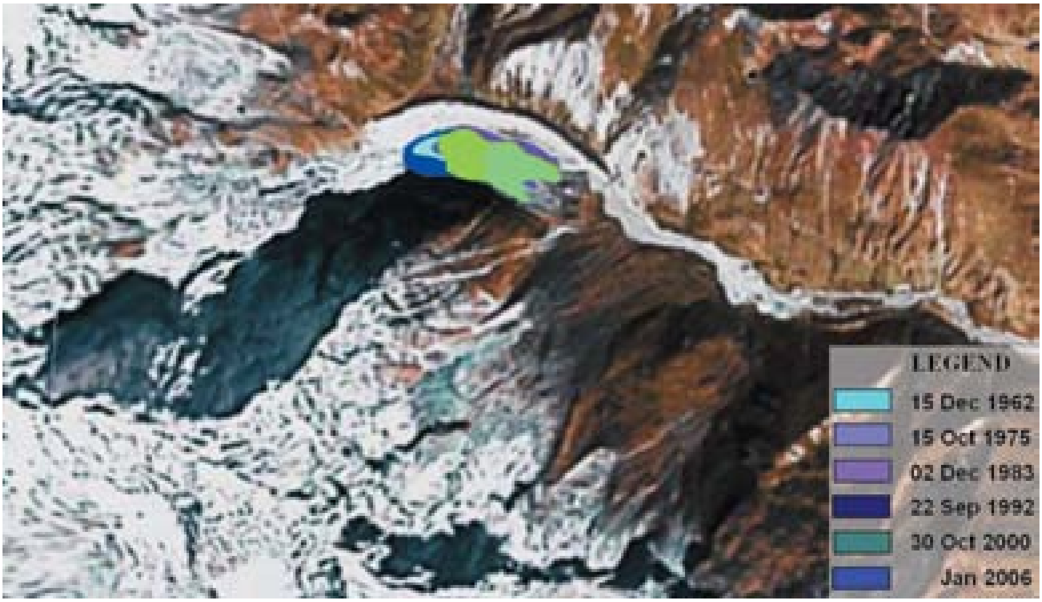


Figure 3.5: Development of Dig Tsho glacial lake between 1962 and 2005

Local witnesses reported that the flood surge front moved rather slowly down the valley as a huge black mass of water and debris. The mean velocity of the surge front was 4-5 m^3s^{-1} (Vuichard and Zimmermann 1987). In some places, people were able to cross the river over suspension bridges whilst the water rushed below. Multiple surges were also reported, for example, the bridges at Jorsalle, Phakding, and Jubing were not destroyed until 30–90 minutes after the passage of the initial surge. The most significant impact of the GLOF was the complete destruction of the newly built hydropower station at Thame, (Figure 3.6) which had cost an estimated US $1.5 million.

The consequences of this GLOF were devastating, both socially and economically. Individual families directly hit by the surge lost their property and holdings, houses, and cattle. About 30 houses in the village were reported to be lost; in a few cases the properties could be salvaged, but this was more the exception than the rule. Villagers lost their subsistence base as well since their cultivable land and forest were also destroyed. Moreover, the tourist economy was affected because tea stalls and lodges were cut off due to the destruction of trails and bridges. About 14 bridges from Mingbo to Jubing village were washed away by the surge.


Figure 3.6: The Thame Hydropower Project a) before the GLOF (4 April 1985) and b) after the GLOF (10 October 1985)

Photos from a recent field study of the Lake Dig Tsho (Figure 3.7) reveal the following:

- Lake Dig Tsho shows evidence of past outburst events.
- The riverbed is composed mostly of boulders and cobbles.
- The lake is no longer hanging and the Langmoche River begins directly from the lake without any spillway.
- The Langmoche glacier (mother glacier of Lake Dig Tsho) is in a hanging position so avalanches or rock/ice falls cannot be discarded from the Langmoche glacier. Debris fall in the lake and possible splash of lake water overtopping the moraine could easily accommodate the debris flow as the outlet of the lake is wide enough.
- There is no indication of lateral moraine movement that could block the lake in the future.
- Available data shows no indication of lake growth since 1992. Further lake growth appears unlikely since the outlet is wide enough and the lake has extended down to the hard rock base glacier snout.

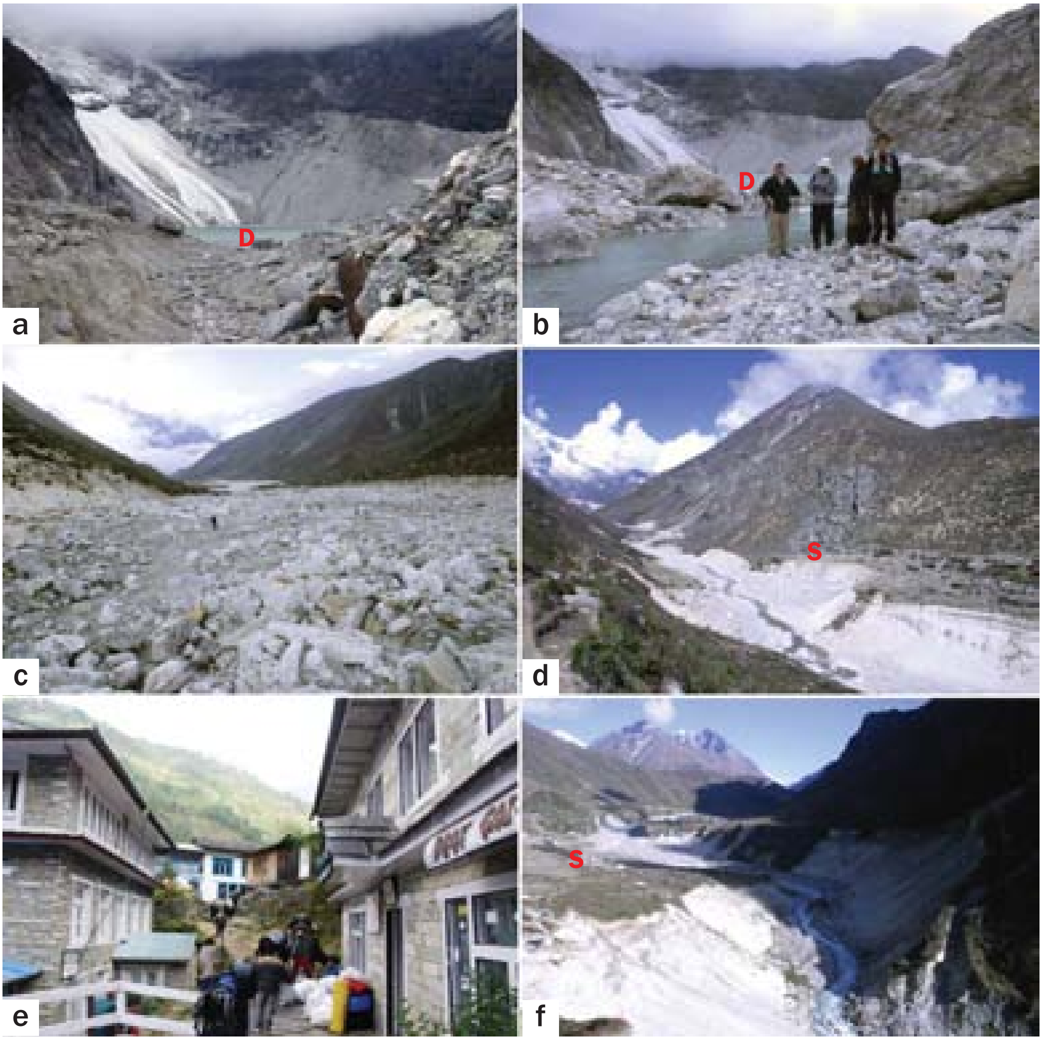


Figure 3.7: Lake Dig Tsho (D) in the Langmoche valley and settlements (S): a) Hanging Langmoche Glacier, Dig Tsho, and outlet of the lake after 1985 GLOF; b) Gentle gradient of the lake outlet through the debris; c) Wide valley downstream; d) Nearest settlement (about 3 km downstream) in the Langmoche valley; e) Phakding village situated on the lowest terrace of the Dudh Koshi River; f) Erosion from 1985 Dig Tsho GLOF at Thamo Teng village

Lake Imja Tsho

Most of the supraglacial lakes formed in the 1960s have now become moraine-dammed lakes due to glacier retreat. The Imja glacial lake is an example of one such lake and has been identified as one of the potentially more dangerous lakes in the Nepal Himalaya. The lake is formed within moraines on all sides and is rapidly extending towards the glacier snout. The end moraine of Lake Imja Tsho is 600m wide. It has an extensive dead ice core, which is often exposed, particularly near the outlet (Figure 3.8). Watanabe et al. (1994 and 1995) reported rapid melting of the debris-covered ice and significant changes in its outlet position.

The catchment of Lake Imja Tsho occupies the northeastern part of the Dudh Koshi sub-basin. The lake itself is located at the toe of its parent glaciers (Imja and Lhotse Shar at 27°59'17" N latitude and 86°55'31" E longitude; Figure 3.9). The Lhotse Shar glacier flows in a south-westerly direction; its highest altitude is 7590m (Peak 38). The Imja glacier is oriented in a north-westerly direction and its highest altitude is 7168m (Peak Baruntse); the terminus of the Imja glacier itself is at about 5100m. These two glaciers coalesce approximately 3.5 km above the terminus and flow westwards just beneath the trekking path to Peak Imjatse (Island Peak 5173m). The Amphu Lapcha glacier, which flows in a northerly direction, is also in the vicinity and falls within the catchment of Imja Lake; however, it is not in direct contact with the lake itself.

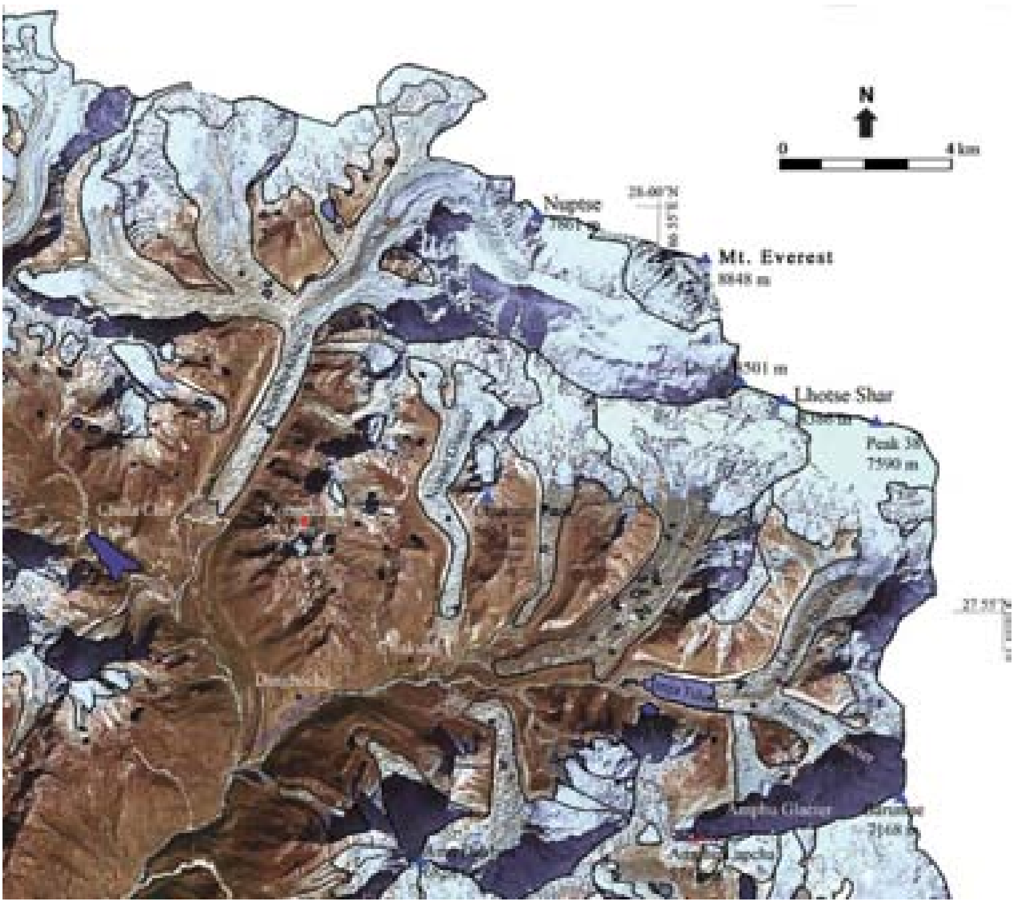


Figure 3.8: Lake Imja Tsho and surrounding glaciers, base image IKONOS

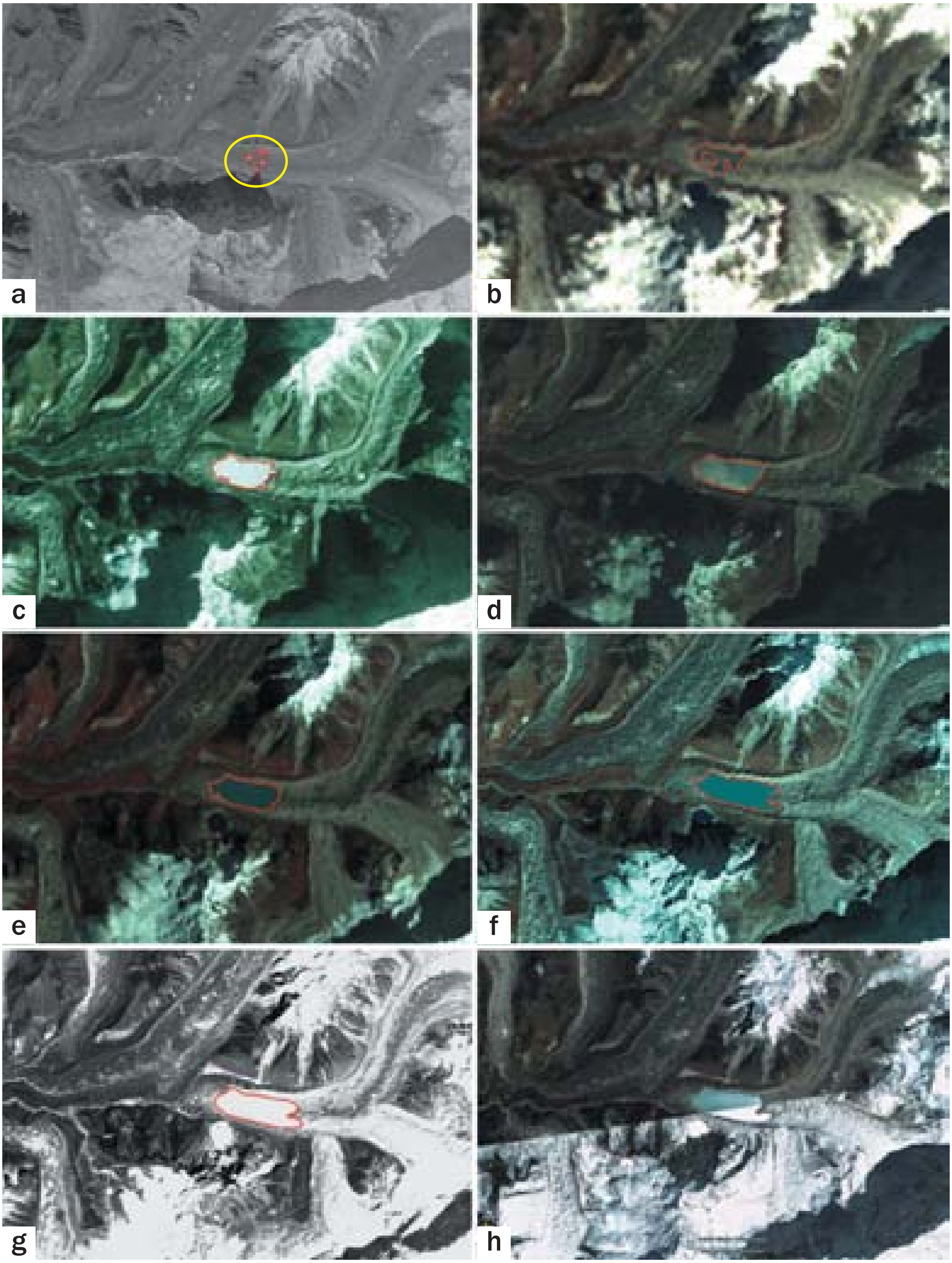


Figure 3.9: Satellite images taken on different dates showing the size of Lake Imja Tsho, see Table 3.6 for details: a) Corona (15 Dec 1962); b) Landsat MSS (15 Oct 1975); c) Sp. Shuttle (02 Dec 1983); d) Landsat5 TM (11 Dec 1989); e) Landsat5 TM (22 Sep 1992); f) Landsat 7 etm+ (30 Oct 2000); g) LISS 3 (19 March 2001); h) Google Earth (Jan 2006)

This lake has a history of rapid growth. Unlike Lake Dig Tsho, as shown in the Corona image of 1960 Lake Imja Tsho did not exist in the early 1960's when the area showed only a few small supraglacial ponds (Figure 3.10). The lake began growing in earnest after reaching an area of 0.3 sq.km in 1975; since then its growth has been quite rapid and it attained areas of 0.56, 0.63 and 0.77 sq.km in 1983, 1989 and 2000 respectively. The lake area was 0.83 sq.km from the field survey in 2001 (Yamada 2003) and 0.86 sq.km in 2002 (GEN and CREH 2006). As the area increased, the average depth of the lake diminished from 47m in 1992 (Yamada 1998) to 41.6m in 2002 (GEN 2006) (note that this same study reported a maximum depth of 90.5m in 2002). The volume of water stored in the lake was estimated at 28 million cubic metres in 1992 and 35.8 million cubic metres in 2002. The lake was formed by damming of the debris-covered ice core; hence continuous expansion of the lake is anticipated due to melting of the ice core as a result of global warming. The thickness of the ice core is about 150m near the glacier snout and disappears at the edge of the end moraine (GEN and CREH 2006).

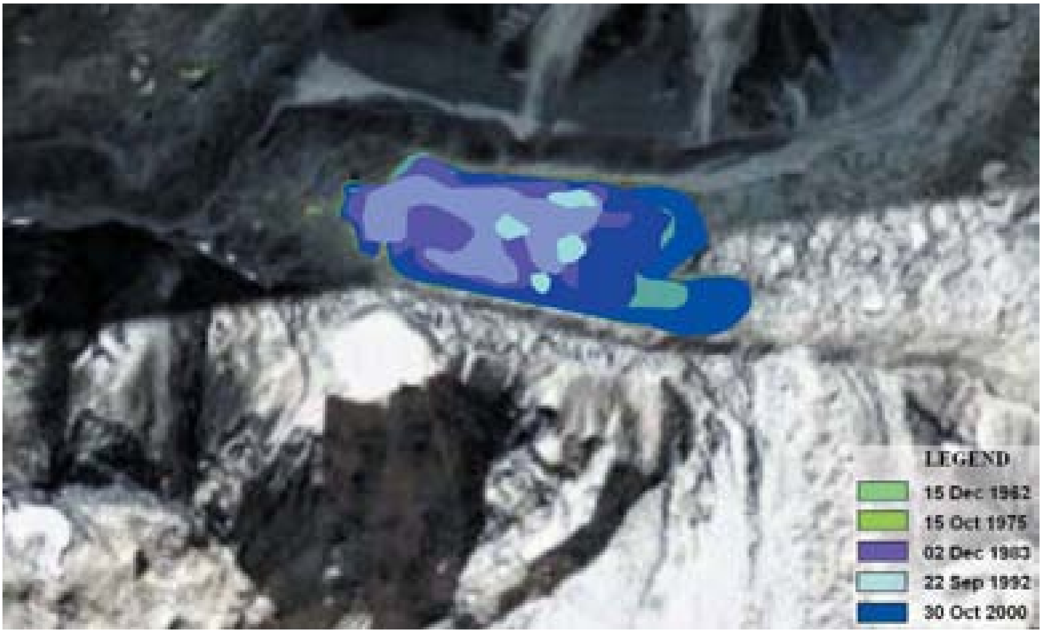


Figure 3.10: Development of Lake Imja Tsho from 1962 to 2006, base image IKONOS

A temporal series of satellite images (from 1962 to 2006) and field verification data show the expansion of the lake from 1962 (Figure 3.10). The lake expanded at an average rate of 42m per year between 1962 and 2001; from 2001 onwards, the rate of change increased to about 74m per year (Table 3.6). The lake has increased in area from 0.82 sq.km in 2001 to 0.94 sq.km in 2006 and in length from 1647 to 2017m during the same period. A recent field visit in October 2006 revealed extensive calving of the glacier snout. Field photographs show exposed ice cliffs in the glacier snout and many large icebergs on the lake (Figure 3.11). Since Lake Imja Tsho is growing so quickly, mitigation measures to reduce the GLOF risks are urgent.

The water draining from the lake through its natural outlet, which runs over the end moraine, is known as the Imja Khola. This river is an important tributary of the Dudh Koshi River, which eventually merges with the Bhote Koshi River below Namche Bazar. Rivers mostly flow through narrow sections with many settlements on the lower and upper terraces (Figure 3.12).

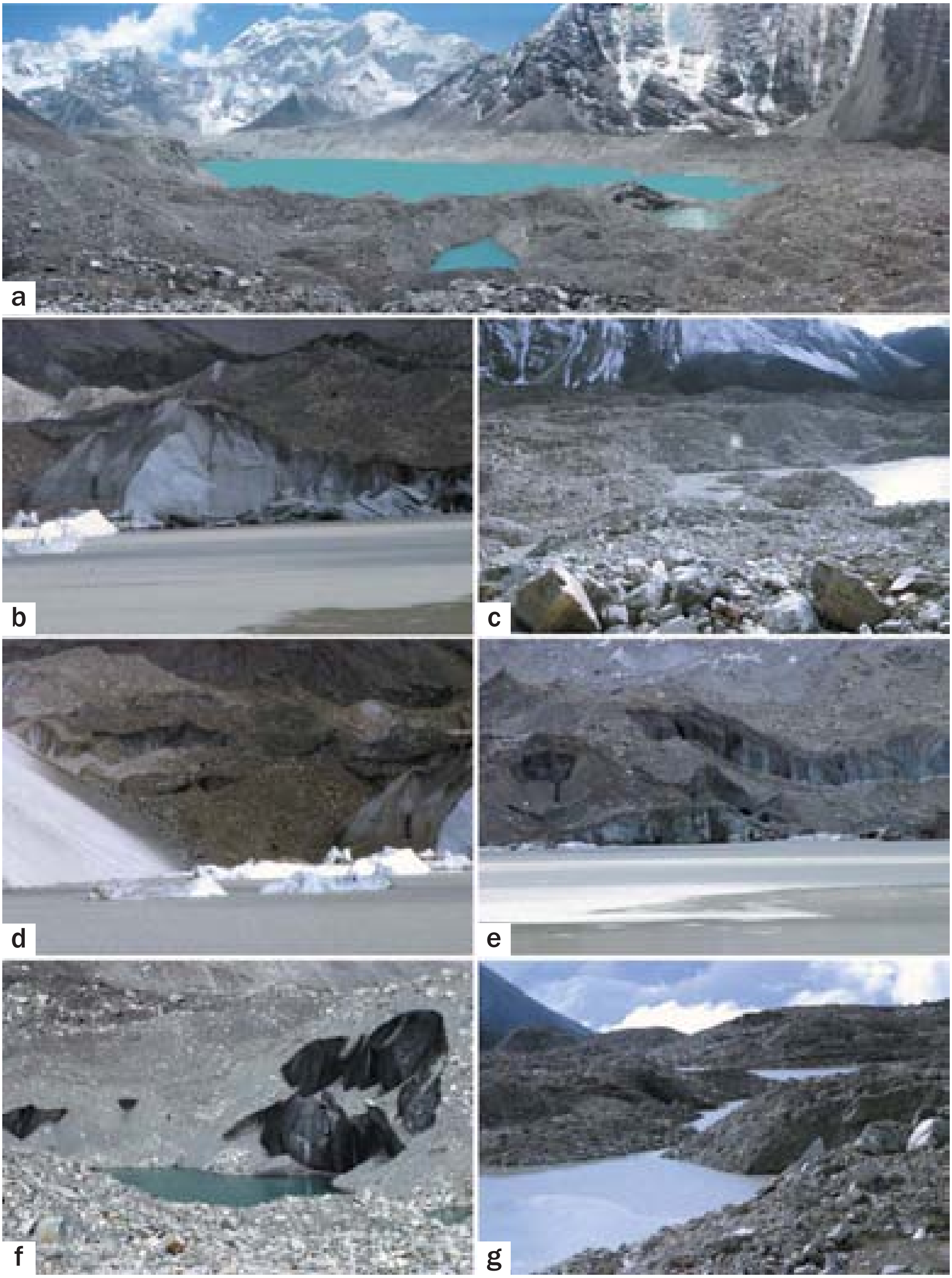


Figure 3.11: Lake Imja Tsho and surrounding environment (Photo: 15 Oct 2006): a) Panoramic view of Lake Imja Tsho; b) Ice cliff at the snout of Imja Glacier; c) Hummocky pattern of moraine indicating dead ice underneath; d) Ice scarps at the glacier snout and icebergs on lake; e) Ice cliff at the terminal moraine; f) Dead ice and a small supraglacial pond; g) Many connected supraglacial ponds

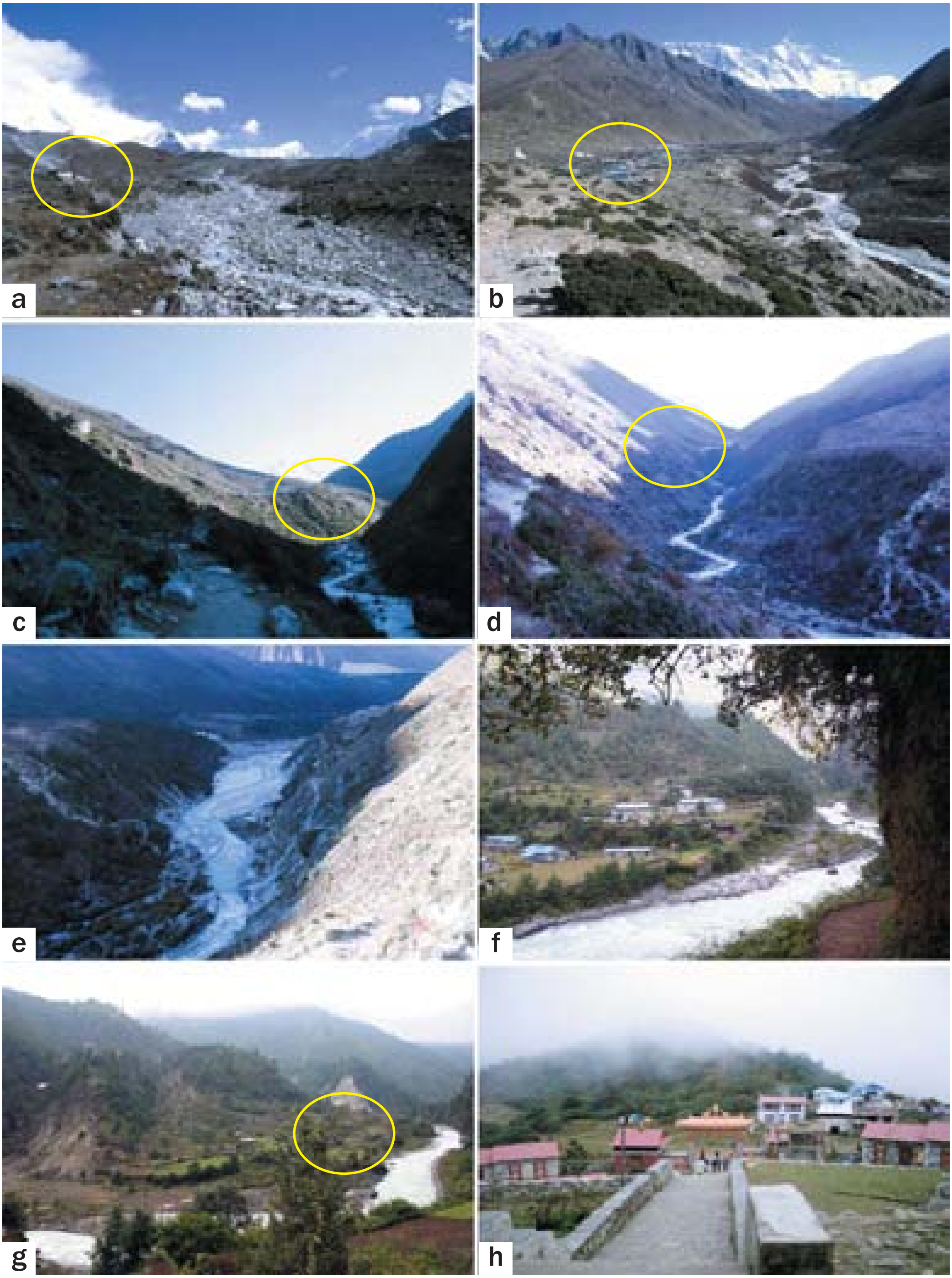


Figure 3.12: Downstream villages of Lake Imja Tsho: a) Chhukung village adjacent to Lake Imja Tsho; b) Dingboche village (7.5 km from Imja); c) Syomare village; d) Pangboche village (13.6 km from Imja); e) Pangboche village (close up view); f) Thulo Gumela village near Phakding village; g) Chutawa village; h) Tengboche village

Table 3.6: **Increase in size of Lake Imja Tsho as observed from satellite images of various years**

Satellite type and year	Area (sq m)	Area difference (sq m)	Length (m)	Length difference (m)	Total length difference (m)	Average growth rate (m/year)
Corona 1962	27,916		55			
Landsat MSS 1975	309,573	281,657	619	564		
Space Shuttle 1983	568,824	259,251	1137	518		
Landsat5 TM 1989	633,214	64,390	1266	129	1592*	42*
Landsat5 TM 1992	635,945	2,731	1271	5		
Landsat7 etm+ 2000	775,065	139,120	1550	279		
LISS3 2001	823,553	48,488	1647	97		
Google Earth 2006	940,722	117,169	2017	370	467**	74**

Note: *between 1962 and 2001, ** between 2001 and 2006

Glacial lakes in the Pho Chu sub-basin of Bhutan*

Pho Chu is a sub-basin of the Puna Tsang Chu basin and one of the largest sub-basins in Bhutan. (Other sub-basins in the Puna Tsang Chu basin include the Sunkosh, the Dang Chu and the Mo Chu, the Dang Chu being devoid of glaciers.) Mool et al. (2001b) mapped 549 lakes in the Pho Chu sub-basin from topographic maps of the 1960s in the Bhutan Himalaya. Some satellite images (LandSat TM) of a much later period were also used where maps were not available or were of poor quality. The present study was carried out using the NaturalVue of EarthSat satellite images of 2000 and 2001. Comparison of the data shows that over time some new lakes have formed and some previously existing lakes have disappeared. New lakes were identified from the satellite images; similarly, satellite images helped verify that some previously identified lakes, especially supraglacial ones, have now disappeared.

Figure 3.13 shows the distribution of glacial lakes in the Pho Chu sub-basin. In the 1960s, lakes covered an area of 23.49 sq.km; by 2001 the overall area covered by lakes in this sub basin increased to about 25.45 sq.km (Figure 3.13), growth of about 8 per cent. Over the 40 years, a total of 175 lakes have either dried up or become so small that they cannot be mapped. Some 82 new lakes have been formed and are numbered serially from pho_gl_550 to pho_gl_631.

Most of the glacial lakes formed at glacier tongues are increasing in size. Examples of some major lakes are given in the Table 3.7. Among these nine glacial lakes, Pho_gl 209 (Lake

Table 3.7: **Area change of major glacial lakes in Pho Chu sub-basin (2001-2006)**

Lake ID	Area in 2001 (m^2)	Area in 2006 (m^2)	Area change %)	Remarks
Pho_gl_84	214,078	743,187	247.2	Increased
Pho_gl_148	454,510	635,180	39.7	Increased
Pho_gl_163	369,572	241,808	34.5	Decreased
Pho_gl_164 (Tarina Tso)	280,550	439,103	56.5	Increased
Pho_gl_172	33,522	38,139	13.7	Increased
Pho_gl_206	44,194	0		Vanished
Pho_gl_207	15,463	0		Vanished
Pho_gl_209 (Raphstreng Tso)	145,949	1,240,131	749.7	Greatly increased
Pho_gl_210 (Luggye Tso)	769,800	1086411	41.1	Increased

*Contributed by D.R. Gurung and Karma Toeb

Figure 3.13: Distribution of glacial lakes in the Pho Chu sub-basin, Bhutan

Raphstreng Tso) and Pho_gl 84 have grown in area by about 750 and 250 per cent respectively, whereas two supraglacial lakes from the Bechung glacier have disappeared from the satellite images of 2000–2001.

Lakes Luggye Tso, Raphstreng Tso, Thorthormi Tso and Tarina Tso

The partial breaching of Lake Luggye Tso in 1994 caused a catastrophic GLOF, the memory of which is still fresh in the minds of people who witnessed it. This GLOF will in all likelihood go down in the history of floods in Bhutan as the most catastrophic event ever recorded both in terms of its magnitude and in terms of the damage it wreaked on the lives, property, and infrastructure of the people downstream. The severity of this event prompted the Department of Geology and Mines (under the Ministry of Trade and Industry, Royal Government of Bhutan), to initiate a number of research activities on the glaciers and glacial lakes in the country.

Numerous studies were conducted on glacial lakes in Bhutan as part of joint Japan-Bhutan, India-Bhutan, and Austria-Bhutan projects from 1995–2004. These studies led to many scientific articles highlighting the risks associated with the lakes, discussing the mechanisms of lake expansion, and assessing the stability of the lakes. Previous sections cited some of these. This section presents different scenarios regarding lake expansion and draws both from earlier work by different experts and from the results of the present work. The discussions focus mainly on the lakes in the Pho Chu basin.

The first detailed work on the expansion of glacial lakes in the Bhutan Himalaya was a time-series of sketches of the major glacial lakes in the Lunana region by Ageta et al. (2000). His subsequent study discussed the evolution of these lakes in detail using maps, photographs, and satellite images. Ageta also studied and discussed the risk that possible outbursts pose on the geophysical environment in and around the lakes.

Luggye Tso

Lake Luggye Tso (Pho_gl 210) is an end moraine-dammed lake in the Pho Chu basin of the Lunana region (Figure 3.14). As late as the 1950s, there were no indications of any lakes being associated with Luggye glacier. The first lake appeared only in 1967 (Gansser 1970) as a supraglacial lake and was measured to be 0.02 sq.km in 1968. Figure 3.15 shows the lake's development from 1967 to 1994. The depth of Luggye Lake was measured in 2000 and shown to be 142m. This glacial lake suffered an outburst event on 7th October 1994. The GLOF from Lake Luggye Tso caused much damage to the downstream valley, including the religiously important Punakha Dzong. After the breach, the lake continued to grow towards the glacier snout and the glacier continued to retreat; in 2001 the lake area measured 1.12 sq.km (Table 3.8). The exposure of ice cliffs on the glacier snout show calving, which contributes to the expansion of the lake towards the glacier (Figure 3.16). The outlet channel is at the same level as the lake surface and has a gentle slope. Evidenced by its bumpy topography, this terminal moraine has an ice core. Both the continuous sliding of the left lateral moraine at the outlet and the presence of an ice core contribute to the possibility of blocking of the previously breached outlet so that the lake could at some time in the future suffer another GLOF event (Figure 3.17).

If the outlet of Lake Luggye Tso is blocked by landslides from the left lateral moraine it will cause the water level of the lake to rise, risking a GLOF event (Figure 3.17) with serious consequences for the Thorthormi lakes further downstream, especially since the Thorthormi glacier has already weakened the left lateral moraine (Ageta et al 2000). Austrian experts Leber and Hausler (2002) concur about the risk from Lake Luggye Tso. In fact, of the possible scenarios that this group examined during their risk assessment of the Luggye GLOF, the

Figure 3.14: Panoramic view of Lake Luggye Tso and Peak Jamlhari in the background

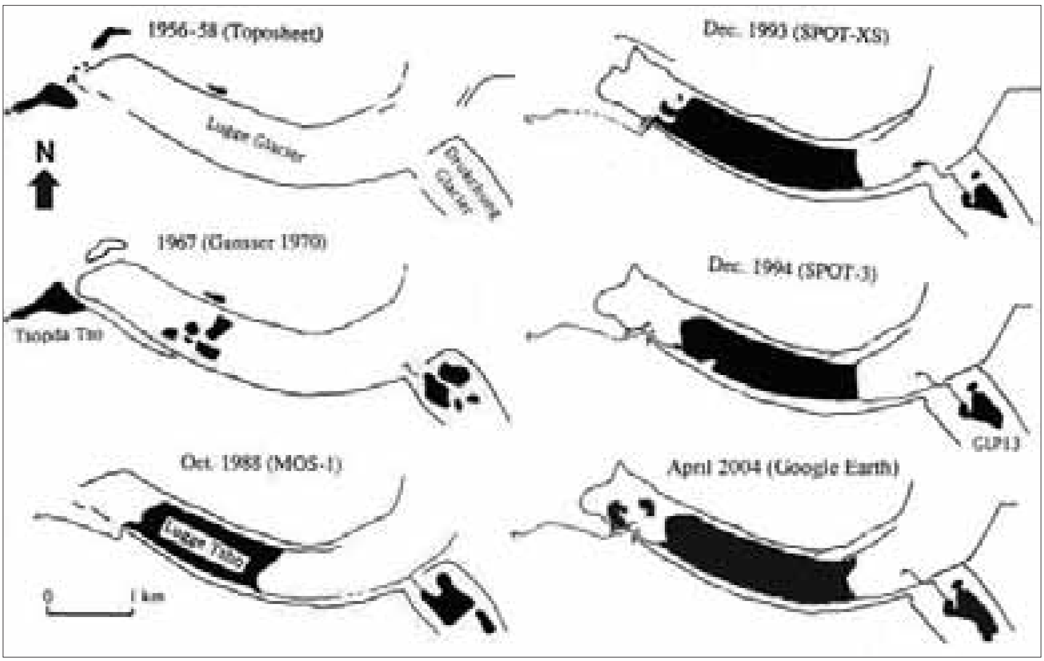


Figure 3.15: Expansion of Lake Luggye Tso (1956-2004) (modified from Ageta et al. 2000)

Figure 3.16: Ice cliff of Luggye glacier snout in contact with Lake Luggye Tso

Figure 3.17: The outlet of Lake Luggye Tso through the end moraine

blockage of the outlet by a landslide from the left lateral moraine was considered the "major risk" (Leber and Hausler 2002). This group recommended that the active sliding zone on the left lateral moraine be stabilised at the outlet to allow free flow of water from the lake. In contrast, Dorji (1996) observed no immediate GLOF risk from this lake because of its wide outlet channel. He commented that the risk of flood from this lake is not imminent as the outlet channel is wide enough to discharge any amount of water that will accumulate.

Raphstreng Tso

Lake Raphstreng Tso (Pho_gl 209) lies at an altitude of 4360m. This lake appeared as a supraglacial lake in a 1958 topographic map; topographic maps from 1960 showed that the lake's area was 0.15 sq.km. In 1986 it was 1.65 km long, 0.96 km wide, and 80m deep (Sharma et. al. 1986). Nine years later, the Indo-Bhutan Expedition of 1995 measured a maximum length of 1.94 km, width of 1.13 km, and depth of 107m (Figures 3.18 and 3.19) (Ageta et al 2000). The depth measured in 1999 was about 100m. Some researchers believe that the lake's present dimensions represent its maximum since the upstream section has already reached the bedrock wall. However, field photographs show that the glacier snout is undergoing extensive calving and that the lake can still expand a few hundred more metres (Figures 3.20 to 3.23).

Prior to the 1994 flood from Lake Luggye Tso, the left lateral moraine was 295 to 410m wide (Bhargava 1995). Toe erosion of the moraine initiated by the flood has reduced the width to 178m. This weakening of the lake barrier and the large size of the lake caused grave concern to the Government of Bhutan. An immediate investigation of the stability of the lake was undertaken in 1995. Three phases of mitigation work were carried out on this lake from 1996 to 1998 in an attempt to lower the water level by about 4m. A channel of 78.5m in length and 36m wide at the outlet was manually widened and deepened at the lake outlet. Nevertheless, the risk of a GLOF cannot be ruled out because a large volume of water is still stored in the lake and a chain effect of GLOFs from other adjacent lakes could occur. An additional threat to the stability of Lake Raphstreng Tso comes from hydrostatic pressure exerted by the

Figure 3.18: Lake Raphstreng Tso in contact with the glacier snout and outlet canal

Thorthormi lakes, from which Lake Raphstreng Tso is separated by only a moraine wall. Similar high risk scenarios have also been reported by Dorji (1996) and Leber et al. (2002).

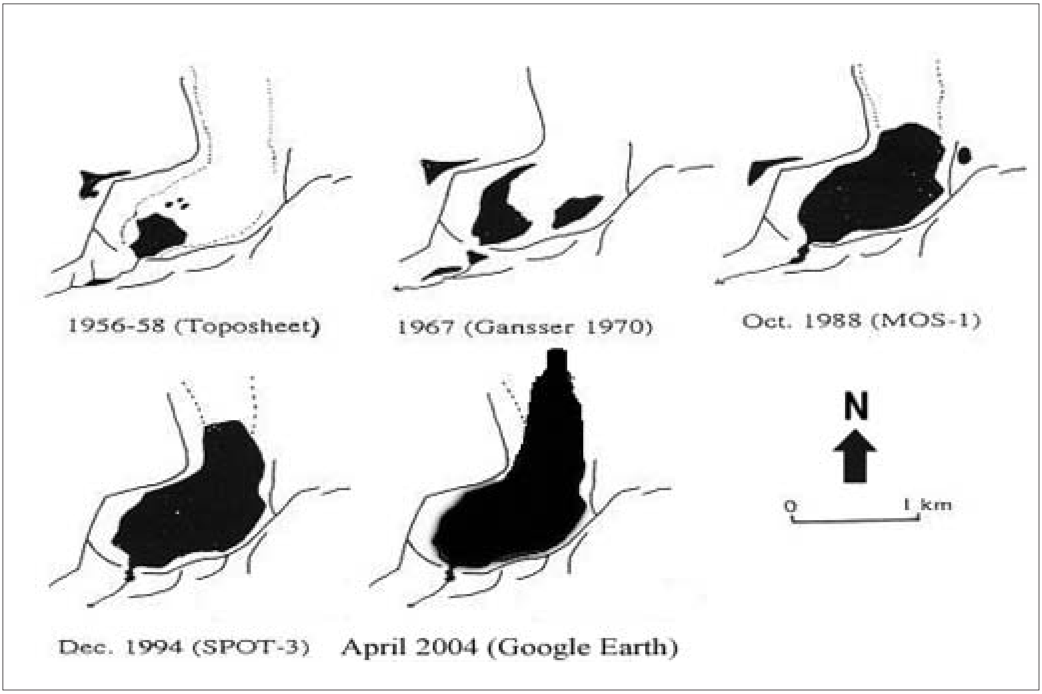


Figure 3.19: Expansion of Lake Raphstreng Tso (1956-2004) (modified from Ageta et al. 2000)

Figure 3.20: Calving of the Raphstreng glacier snout with the expansion of the lake in 2001

Figure 3.21: Raphstreng glacier snout undergoing active calving

Figure 3.22: Lake Raphstreng Tso with newly formed supraglacial ponds on right lateral moraine.

Figure 3.23: Lake Raphstreng Tso with glacier snout. The ripples on the water surface generated by falling ice blocks indicate the active calving of the glacier snout.

Thorthormi lakes

The Thorthormi lakes do not appear in the 1960s maps of the Thorthormi glacier. These supraglacial lakes began to appear on the maps only after 1967. After 1993, many supraglacial lakes became visible, and currently this large glacier contains many supraglacial lakes many of which are merging and growing. The largest of the lakes is Lake Thorthormi Tso. While it does not appear on the 1958 topographic map, some supraglacial lakes are visible on the map reported later by Gansser (Figure 3.24). The Thorthormi terminal moraine (with a width of 30m at its crest) acts as a dam between Lake Thorthormi Tso and Lake Raphstreng Tso. Lake Thorthormi Tso is a supraglacial lake that is 65m higher than Lake Raphstreng Tso and lies directly above it. It is separated from the Pho Chu by a thin, continuously eroding, left lateral moraine. Since Lake Thorthormi Tso is at a higher elevation than Lake Raphstreng Tso, and since the terminal and left lateral moraine are narrow and unstable, this lake and glacier need to be continuously monitored.

Figure 3.24 shows a time series expansion of the Thorthormi lakes from 1956 to 1993. Ageta et al (2000) reported supraglacial lakes on this huge debris-cover glacier in the 1990s. The continuing expansion of these supraglacial lakes was observed in 1998 during the first joint Japan-Bhutan field expedition. This growing lake has a potential for an outburst in the near future for several reasons (Figures 3.25 to 3.28). First, accelerated melting of the ice has been observed; second, there is only a gentle gradient at the snout region; third, the left lateral moraine ridge is being eroded by discharge water from the upstream Luggye Lake; finally, considerable seepage is seen from the left lateral moraine.

Dorji (1996) recommended continuous monitoring of these growing supraglacial lakes. Brauner et al. (2003) conclude from their four-year investigation in the Lunana area that a severe GLOF threat exists in their estimated worst-case scenario in the near future.

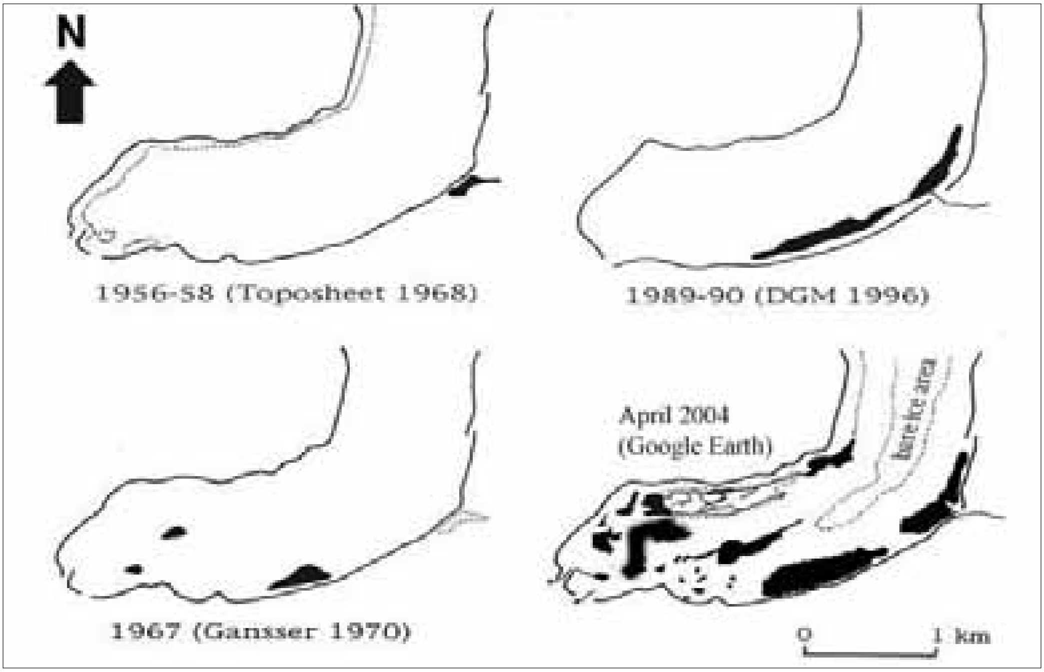


Figure 3.24: Expansion of Lake Thorthormi Tso (1956-2004) (modified from Ageta et al. 2000)

Figure 3.25: Supraglacial lakes formed in the Thorthormi glacier

Figure 3.26: A glacial lake located in the Thorthormi glacier, near the inlet of Lake Luggye Tso

Figure 3.27: A supraglacial lake at the lower left side of the Thorthormi glacier

Figure 3.28: An avalanche at the accumulation zone of the Thorthormi glacier.

Comparison of changes in the three major lakes

The present work attempted to demarcate changes on the glacial lakes in the Lunana area on a decadal basis from 1968 to 2001 in terms of both area and length. The work was based on the 1950s topographic map and different satellite images such as the Landsat_2 (MSS) of 1978, MOS 1 of 1988, Landsat (TM) of 1998, and NaturalVue for 2001 (Figure 2.8). The results are tabulated in Table 3.8 and are shown graphically in Figure 2.9.

As Figure 2.9 indicates, all three major lakes (Raphstreng, Thorthormi, and Luggye) share a common feature – a sudden increase in area at one point of their evolution. It is clear from the same figure that all the lakes except Raphstreng are still expanding and show similar expansion patterns. Drukchung lake breached in the early 1990s (Leber et al. 2002) and the lake area has remained constant since that time (Figure 2.9).

Table 3.8: **Lake length and area changes in the Lunana region (1968 – 2001)**

Lake	Lake area (sq km)				
	1968	**1978**	**1988**	**1998**	**2001**
Raphstreng	0.16	1.02	1.18	1.23	1.23
Thorthormi	0.02	0.13	0.38	1.20	1.28
Luggye	0.02	0.16	0.84	1.06	1.12
Drukchung	*	0.03	0.15	0.12	0.12
	Lake length (m)				
Raphstreng	579.8	1576.6	1830.5	1931.7	1963.4
Luggye	*	*	1595.4	2169.4	2190.9

* data not available

Lake Tarina Tso

Lake Tarina Tso (Pho_gl 164) consists of two lakes – one above the other – at an altitude of 4320m. The lower lake – about 500m long and 300m wide – appears different in size and shape depending on the map. The upper lake clearly shows expansion towards the glacier snout. The outlets of both lakes are clear and drain into the western branch of the Pho Chu. This lake has breached in the past, as evidenced by the breached end moraine, and large debris fan in the downstream area. Although the lake now has a well-defined outlet and is detached from the glacier tongue, its size and the presence of glacial ice on the rocky steep cliff (directly above the lake) are cause for concern.

The second lake lies directly above the lower lake. Shaped like a boomerang, its dimensions are approximately 2 km x 0.3 km, and it is in contact with the glacier tongue resting on a rocky cliff. The outer slope of the end moraine (through which the lake drains) is vegetated and has a gentle slope – there appears to be no immediate danger from this lake.

Lake Tarina Tso (GLP1 as designated by Ageta et al. (2000)) already existed, and was large enough to appear on the 1950 maps (Figure 3.29). GLP1 Lake in 1956/1958 to 1967 gave a clear indication of growing; according to the 1988 maps, however, the lake's shape changed but its size remained more or less constant. The 1989 maps show that the lake had

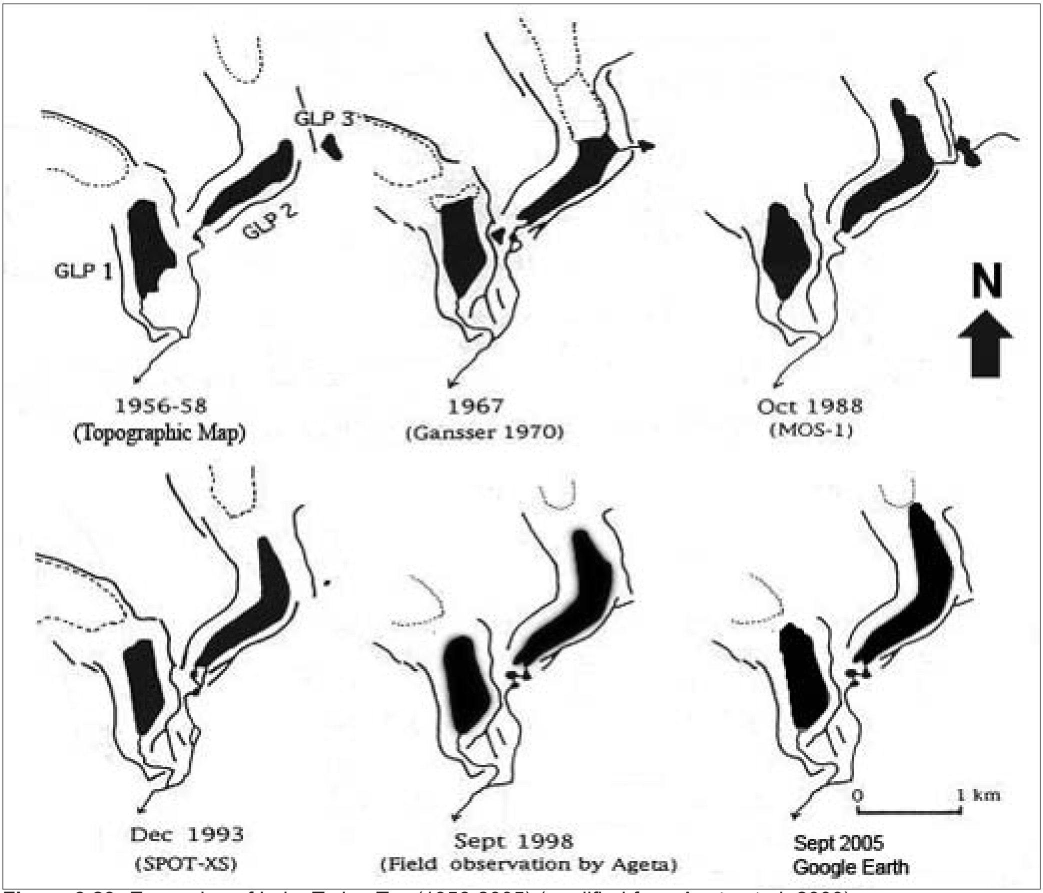


Figure 3.29: Expansion of Lake Tarina Tso (1956-2005) (modified from Ageta et al. 2000)

diminished in size (possibly indicating an outburst event), but in subsequent years the lake is once again expanding. Both lakes have reached their maximum extent, having reached the upstream bedrock wall. A surge wave, resulting from icefall into the lakes, could cause overtopping – the only risk associated with these two lakes (Ageta et al 2000).

Austrian experts made a comprehensive report on the risk assessment of this area. Their assessment of Tarina I (glacial lake point [GLP] 1) states that ice falls from the hanging ice wall could trigger surge waves that might lead to overtopping of Tarina I lake. However, they predict that the impact on the downstream would be low.

As for Tarina II (GLP2), their worst-case scenarios included a chain reaction for a series of events from the glaciers and lakes above this main lake (Figure 3.30). The projected volume of water and sediment it could release to the downstream is estimated to be 3.4 million m^3. However, Dorji (1996) expressed a different opinion and reported that the lakes are safe. In his own words, “Both the lakes in Tarina do not pose any threat of flood”.

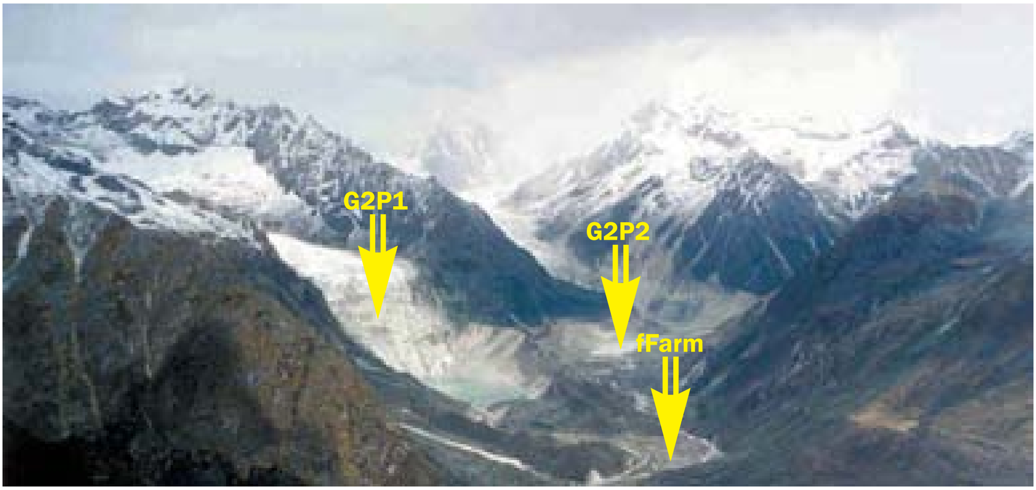


Figure 3.30: Lakes of Tarina and the surrounding glacial environment

Potentially dangerous glacial lakes in Bhutan

Twenty-four lakes were identified as potentially dangerous based on a set of criteria such as water level rise, the associated mother glacier, and the conditions of the dams and topographical features of the surroundings (Mool et al. 2001).

Considering these criteria, five lakes in the Mo Chu sub-basin, eight lakes in Pho Chu sub-basin, seven lakes in the Mangde Chu sub-basin, three lakes in the Chamkhar Chu sub-basin and one lake in the Kuri Chu sub-basin were identified as potentially dangerous. The present work compares changes in these 24 lakes. Data for the earlier inventory were based on the topographic map of the 1960s and the present data are derived from satellite images (Nature vue of 2000 and 2001). The Thorthormi lakes were not significant in terms of area in the 1960s, and were not considered potentially dangerous at that time. However, since they are expanding at a considerable rate because the associated mother glacier is retreating at a high rate, and since they are sandwiched between two other potentially dangerous lakes

(Lake Raphstreng Tso and Lake Luggye Tso), Thorthormi has been added as number 25 on the list of potentially dangerous lakes. Table 3.9 and Figure 3.31 show the changes that have occurred in these lakes in terms of area, and Table 3.10 and Figure 3.32 show the changes that have taken place in their recorded lengths between the 1960s and 2001.

Of the 24 potentially dangerous lakes identified by Mool et al. (2001), only 15 lakes increased in area while the remaining nine decreased in area between the 1960s and 2001 (Table 3.9 and Figure 3.31). Noteworthy are the lakes associated with the retreating glaciers in the Lunana region that are increasing in area.

Figure 3.32 shows the changes that have taken place in terms of length over the time period. In total 19 lakes increased and five lakes remained unchanged in length.

Table 3.9: **Area change of potentially dangerous lakes from Bhutan Himalaya (1960-2000)**

Lake ID	Area (sq km)		Area change	
	1960s	2000	(sq km)	%
Mo_gl_200	0.05	0.08	0.03	60
Mo_gl_201	0.03	0.06	0.03	100
Mo_gl_202	0.03	0.04	0.01	33
Mo_gl_234	0.23	0.21	-0.02	-8.
Mo_gl_235	0.15	0.12	-0.03	-20
Pho_gl_84	0.21	0.74	0.53	252
Pho_gl_148	0.45	0.63	0.18	40
Pho_gl_163	0.36	0.24	-0.12	-33
Pho_gl_164	0.28	0.43	0.15	53
Pho_gl_209	0.14	1.24	1.1	785
Pho_gl_210	0.76	1.08	0.32	42
Pho_gl_211	0.14	0.11	-0.03	-21
Pho_gl_313	0.02	0.22	0.2	1000
Thorthormi (pho_gl_612 to 621)	Numerous supraglacial ponds on the ablation area of Thorthormi glacier are enlarging and becoming interconnected.			
Mangd_gl_99	0.19	0.2	0.01	5
Mangd_gl_106	0.86	1.11	0.25	29
Mangd_gl_270	0.23	0.25	0.02	8
Mangd_gl_285	0.34	0.35	0.01	2
Mangd_gl_307	0.76	0.84	0.08	10
Mangd_gl_310	0.2	0.19	-0.01	-5
Mangd_gl_385	0.47	0.23	-0.24	-51
Cham_gl_198	0.62	0.59	-0.03	-4
Cham_gl_232	0.2	0.18	-0.02	-10
Cham_gl_383	1.03	1.01	-0.02	-1
Kuri_gl_172	0.1	0.15	0.05	50

Note: the conventional signs in the above table represent negative (-) for decrease in area and positive for increase in area.

Table 3.10: **Change in length of potentially dangerous lakes in Bhutan**

Lake ID	Length in 1960s (km)	Length in 2000 (km)	Length change	
			(km)	(%)
Mo_gl_200	0.28	0.53	0.25	89
Mo_gl_201	0.32	0.36	0.04	12
Mo_gl_202	0.32	0.32	0	0
Mo_gl_234	0.79	0.79	0	0
Mo_gl_235	0.56	0.58	0.02	3
Pho_gl_84	0.66	1.56	0.9	136
Pho_gl_148	1.28	1.72	0.44	34
Pho_gl_163	1.2	1.2	0	0
Pho_gl_164	1.09	1.8	0.71	65
Pho_gl_209	0.55	1.95	1.4	254
Pho_gl_210	1.98	2.11	0.13	6
Pho_gl_211	0.65	0.66	0.01	1
Pho_gl_313	0.2	0.92	0.72	360
Thorthormi (Pho_gl_612 to621)	Numerous supra glacial ponds on the ablation area of Thorthormi glacier are enlarging and are becoming interconnected.			
Mangd_gl_99	0.6	0.63	0.03	5
Mangd_gl_106	1.48	1.87	0.39	26
Mangd_gl_270	0.85	0.83	-0.02	-2
Mangd_gl_285	0.79	0.96	0.17	21
Mangd_gl_307	1.8	1.93	0.13	7
Mangd_gl_310	0.57	0.64	0.07	12
Mangd_gl_385	0.53	0.86	0.33	62
Cham_gl_198	1.49	1.66	0.17	11
Cham_gl_232	0.56	0.56	0	0
Cham_gl_383	2.64	2.75	0.11	4
Kuri_gl_172	0.85	0.85	0	0

Note: the conventional signs in the above table represents negative (-) for decrease in length and positive for increase in length.

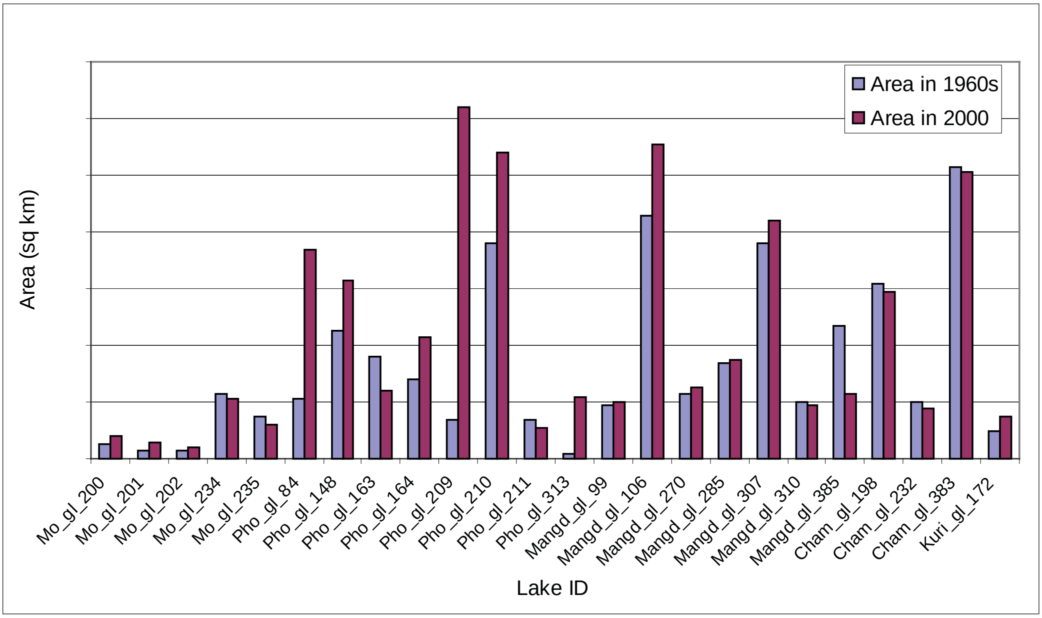


Figure 3.31: Area change of the 24 potentially dangerous lakes in Bhutan from the 1960s to 2001

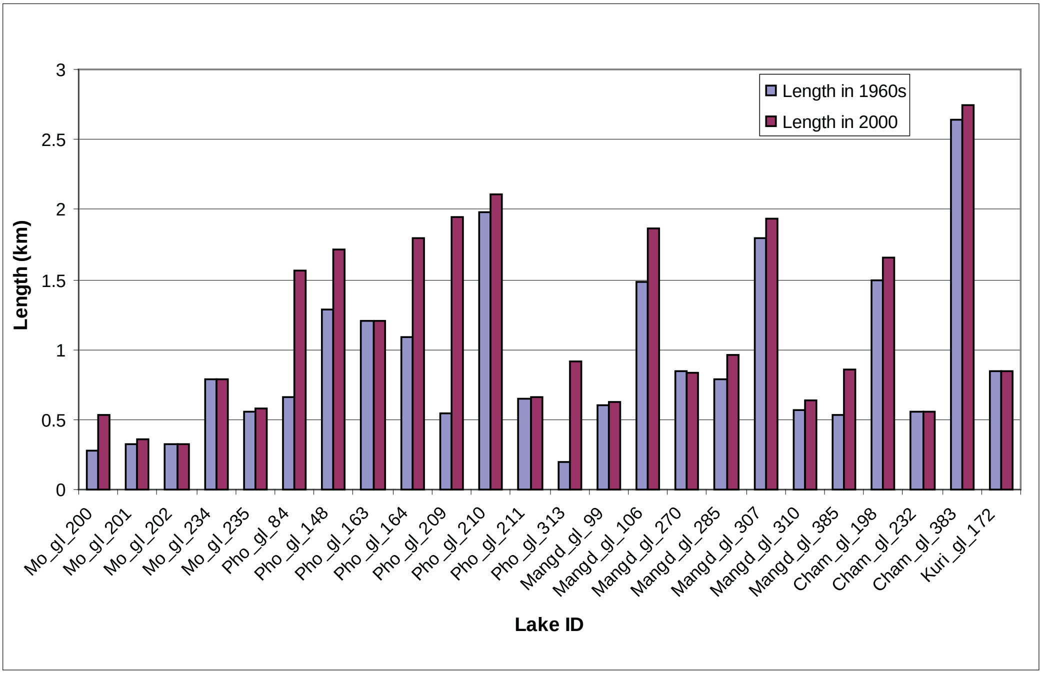


Figure 3.32: Length change of the 24 potentially dangerous lakes in Bhutan from the 1960s to 2001

Comparison of changes in glacial lakes in Bhutan and Nepal

Thirty seven per cent of the lakes which existed in the Dudh Koshi sub-basin of Nepal in the 1960s have now disappeared; similarly 32 per cent of those originally measured in the Pho Chu basin of Bhutan have also disappeared. Most of the lakes that disappeared were either not glacier-fed or were minor supraglacial ponds which merged to form a single large lake. The smaller lakes (less than 2500 sq.m in area) could not be mapped due to the low resolution of the satellite image used in this study as compared to the previous study based on larger scale topographic maps (Mool et al. 2001a, b). Although the number of lakes has decreased, the overall lake area in the sub-basins has increased by 21 per cent in Nepal and 8 per cent in Bhutan. As the area of these lakes – which are associated with glaciers – continues to increase, their downstream areas are at risk for GLOF events. These potentially dangerous lakes as well as their associated glaciers should continue to be monitored.

Chapter 4
Hydrodynamic Modelling of Glacial Lake Outburst Floods

To better understand the impacts that a GLOF can have on the downstream valleys, an attempt was made to simulate one GLOF event each in Nepal and Bhutan using hydrodynamic modelling.[1] The two models are discussed below.

Modelling a Lake Imja Tsho GLOF

Lake Imja Tsho is an ice core moraine dammed lake that was estimated to cover about 0.94 square km in 2006. The details of the lake are given in Chapter 3. A short review of materials and methods is given below and the main outcomes of the modelling are discussed.

The topographic information needed for the hydrodynamic modelling was derived from topographic maps published by the topographic Survey Department of Nepal in 1996. The digital elevation model (DEM) was derived from 40m interval contour maps and the river valley cross-sections were derived from the DEM. Bathymetric information for the Lake Imja Tsho was derived from the results of the bathymetric survey of 2001 conducted jointly by Glaciological Expedition in Nepal (GEN) and the Department of Hydrology and Meteorology, Nepal (DHM).

The geometric and hydraulic information from the DEM was extracted using the US Army Corps of Engineers (USACE) software HEC GeoRAS v3.1.1. First, the stream centreline was established from the DEM. The banks were digitized based on topographic maps and high-resolution IKONOS imageries. The GLOF simulation encompasses the entire area from the outlet of the lake and terminating at the boundary of the Dudh Koshi basin buffer zone. The length derived for the Lake Imja Tsho GLOF simulation was 45.22 km. River cross-sections were established at 200m intervals, a total of 209 cross-sections. The cross-sections used were about 1700m wide since this is the maximum HEC GeoRAS width for the DEM resolution used. AutoCAD was used to automatically delineate the cross-section lines at regular intervals. In a few cases, the automatically delineated cross-section lines had to be manually edited because they overlapped each other where there was a sharp meander in the streamline.

Dam breach model

A dam breach model developed by the National Weather Services (NWS-BREACH) was used to simulate the outburst hydrographs. The inputs required by this model include the geometry and some geotechnical parameters of the moraine dam, the lake area, and the lake depth information. The geometric data of the Dig Tsho moraine dam were taken from the DEM. Since geotechnical parameters for the lakes were not available, parameters from the Tsho Rolpa were used (DHM 1996). This substitution is justified because of the many similarities

[1] Contributed by B. Bajracharya, A.B. Shrestha, L. Rajbhandari, P.R. Maskey, and S.P. Joshi

Table 4.1: **Parameters and input data for NWS-BREACH model for Lake Imja Tsho**

Parameter	Value
Lake surface area	0.86 km^2
Lake maximum depth	90m
Dam top altitude	5030m
Dam bottom altitude	4960m
Dam inside slope	1:06
Dam outside slope	1:08
Dam width	600m
Dam length	650m
d_{50}	1 mm
d_{90}	300 mm
d_{30}	0.1 mm
$d_{90/30}$	3000
Unit weight	2000 kg m^{-3}
Porosity	0.4
Manning's n of outer core of dam	0.15
Internal friction angle (ø)	34
Cohesion	0

between the two cases. Geometric data of the moraine dam of Lake Imja Tsho was based on information from a detailed survey conducted by Japanese scientists (Watanabe 1995) and the lake area-depth information was based on the bathymetric data of the lake (GEN 2001). Some parameters and important data used in the NWS-BREACH model are given in Table 4.1.

After the GLOF hydrograph was derived from the NWS-BREACH model, the nature of flood propagation in the downstream was derived from hydrodynamic modelling. For this, the geometric and hydraulic data from HEC GeoRAS was exported to HEC-RAS, a single dimensional hydrodynamic model developed by the US Army Corps of Engineers, Hydrologic Engineering Center (HEC) (USACE 2004). A flow hydrograph, derived from NWS-BREACH, was given as the upstream boundary. The downstream boundary condition was given as a discharge rating curve. The discharge rating curve was derived by the Slope-Area method using Manning's equation for open channel flow. For this, the last two cross-sections were used. AutoCAD was used to calculate the channel width, area, and wetted perimeter at different water levels, necessary for the Slope-Area computation.

Although HEC-RAS was able to simulate the flow at steady flow conditions, it could not simulate the unsteady flow conditions due to instability in the model. Even after discussion with the constructors, it was not possible to resolve the problem, probably because of the extremely steep river slope. As simulating the unsteady river flow was essential to predict the GLOF outflow, another model was needed. A one-dimensional hydrodynamic model developed by the National Weather Services U.S.A. (NWS-Flood Wave) was used. This model demands very detailed and elaborate configurational inputs, in terms of model parameters, input data, geometric information, and others. The modelling was performed using 42 cross-sections re-sampled at about 1000m intervals. Although the simulation completed successfully, it was noted that attempts to increase the number of cross-sections prevented the model from converging – most probably due to rapid contraction and expansion.

While NWS-Flood Wave successfully simulated the GLOF, its outputs were limited to numeric results and line-graphs. Additional simulations are required to generate flood maps. The numeric outputs of NWS-Flood Wave were fed into the HEC-RAS model that was set up to run under steady flow conditions. All the cross-sections from the NWS-Flood Wave were used as flow change points in HEC-RAS. The peak discharges at these cross-sections, calculated by NWS-Flood Wave, were used as the flow inputs for the respective points. The unsteady flow was calculated with 209 cross-sections initially derived for the HEC RAS simulation. This resulted in relatively smooth high flood levels along the river reaches. The high flood level data for all cross-sections were exported back to HEC Geo-RAS, which has an in-built internal algorithm to generate inundation and flood depth maps.

Results of hydrodynamic modelling

For this study, only one scenario of dam breach was considered; the GLOF hydrograph is shown in Figure 4.1. The outputs of the dam breach produced using NWS-BREACH are given in Table 4.2; The rather long predicted duration of the outflow is most probably due to the width of the Lake Imja Tsho moraine dam.

The peak flow and maximum flood depth along the river reaches are shown in Figure 4.2. The attenuation of Lake Imja Tsho GLOF is much dampened. The peak discharge of 5400 m^3s^{-1} at the outlet of the lake is sustained for a considerable distance. Note that for up to 30 km from the lake (16 km from the boundary of the Dudh Koshi basin) the peak flow attenuation still follows a convex curve. This remarkably sustained peak flow along the reach is attributed to the relatively spread-out outflow hydrograph.

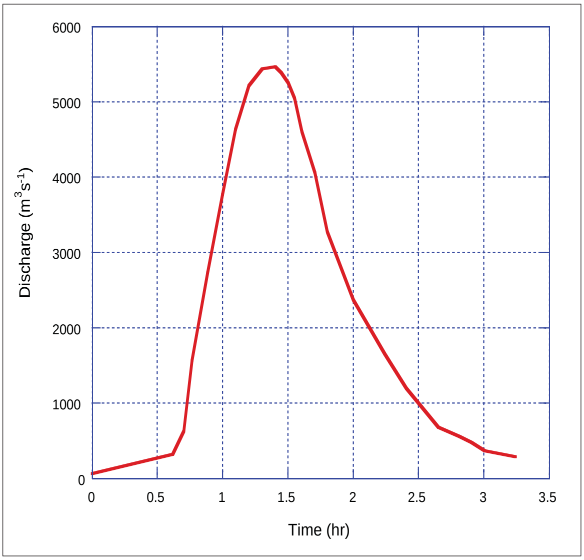


Figure 4.1: GLOF hydrograph of Lake Imja Tsho produced using NWS-BREACH

Figure 4.2, bottom, shows the high-flood depth along the rivers. Many closely spaced peaks are found throughout the river reaches. Higher flooding depths occur at the narrower river sections. Such narrow sections can be found at the gorges downstream of Tengboche and upstream of Namche Bazar, and at the confluence of the Dudh Koshi and Bhote Koshi.

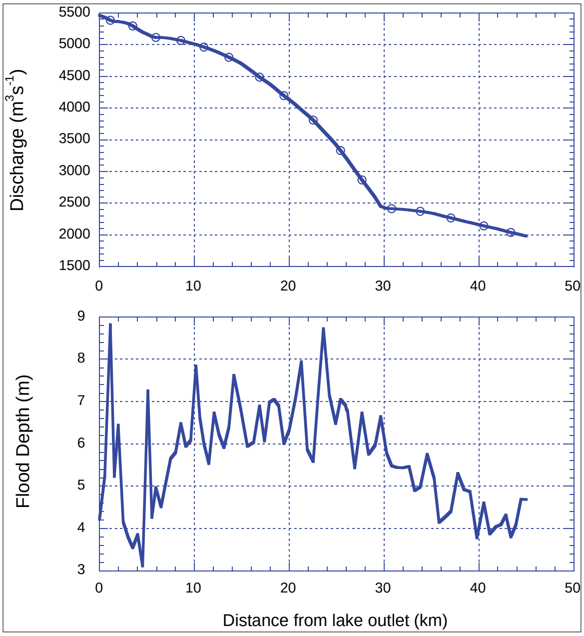


Figure 4.2: Estimated peak flow (top) and high flood depth (bottom) in the river

The spatial distribution of the flood was analysed by preparing inundation maps for the high flood level along the

Table 4.2: **Main outputs of NWS-BREACH for Lake Imja Tsho**

Output	Value
Maximum outflow (Q_{max})	5463 m^3s^{-1}
Duration of outflow (T_{out})	3.2 hr
Initial water level	5030.6m
Final water level	4982.3m
Final depth of breach	65.2m
Final width of top of breach	30.5m

Table 4.3: **Estimated flood arrival time and discharge from Imja GLOF**				
Place	**Chainage (km)**	**Time (min)**	**Discharge (m^3s^{-1})**	**Flood depth (m)**
Imja lake outlet	0.0	0.0	5461	
Dingboche	7.52	13.9	5094	5.8
Orso	11.55	18.8	4932	5.5
Pangboche	13.65	21.3	4800	7.6
Larja Dovan (confluence)	25.94	34.8	3223	6.9
Bengkar	29.67	38.8	2447	6.6
Ghat	34.56	46.4	2355	5.8

river. The inundation maps reveal the spatial extent of the flooding as well as the depth of the flooding along the river reach (Table 4.3). This table helps estimate the arrival time of the flood – information that can be useful in preparing to reduce the GLOF risk. Simulated inundation maps for the Lake Imja Tsho GLOF are shown in Figure 4.3.

Limitations

The cross-sections and longitudinal profiles of the stream were derived from a 5m resolution DEM generated from 40m interval contour maps. The DEM, although fine in resolution, cannot capture all the intricacies of the topography and often leads to erroneous results. The accuracy of geotechnical and hydraulic data all contribute to the accuracy of the model; since in this study, all of the model parameters were either estimated or taken from similar studies, the resultant model can continue to be improved as improved geotechnical field data become available. Another limitation is that only a single scenario was considered for each GLOF simulation. Ideally, a systematic sensitivity analysis is first needed to identify the most sensitive parameters; subsequently, several outburst flood routing scenarios should be considered.

Modelling a Lake Raphstreng Tso GLOF

The topographic information for the model was obtained from 1 inch to 1 mile topographic maps. The cross-sections for the dam break model were prepared from the topographic map for the area, which extends from Lake Raphstreng Tso to Hebesa-Dema for a length of about 115 km and includes the Punakha settlement 84.9 km downstream (Table 4.4). The river valleys were classified into three types based on the width of the cross sections: wide (>500m), medium (260–500m), and narrow (<260m). Typical cross-sections with high flood levels are given in Figure 4.4.

Based on topographic maps, Lake Raphstreng Tso occupied an area of 0.15 km^2 in 1960, which by 1986 had expanded to 1.65 km (maximum length) x 0.96 km (maximum width) and had become 80m deep (Sharma et al. 1986). The Indo–Bhutan Expedition of 1995 reported continued expansion, and recorded dimensions of 1.94 km x 1.13 km with a depth of 107m. In 2001, the lake area was 1.23 sq.km (Table 3.8), with an estimated volume of 20.3 million cubic metres (Table 4.5).

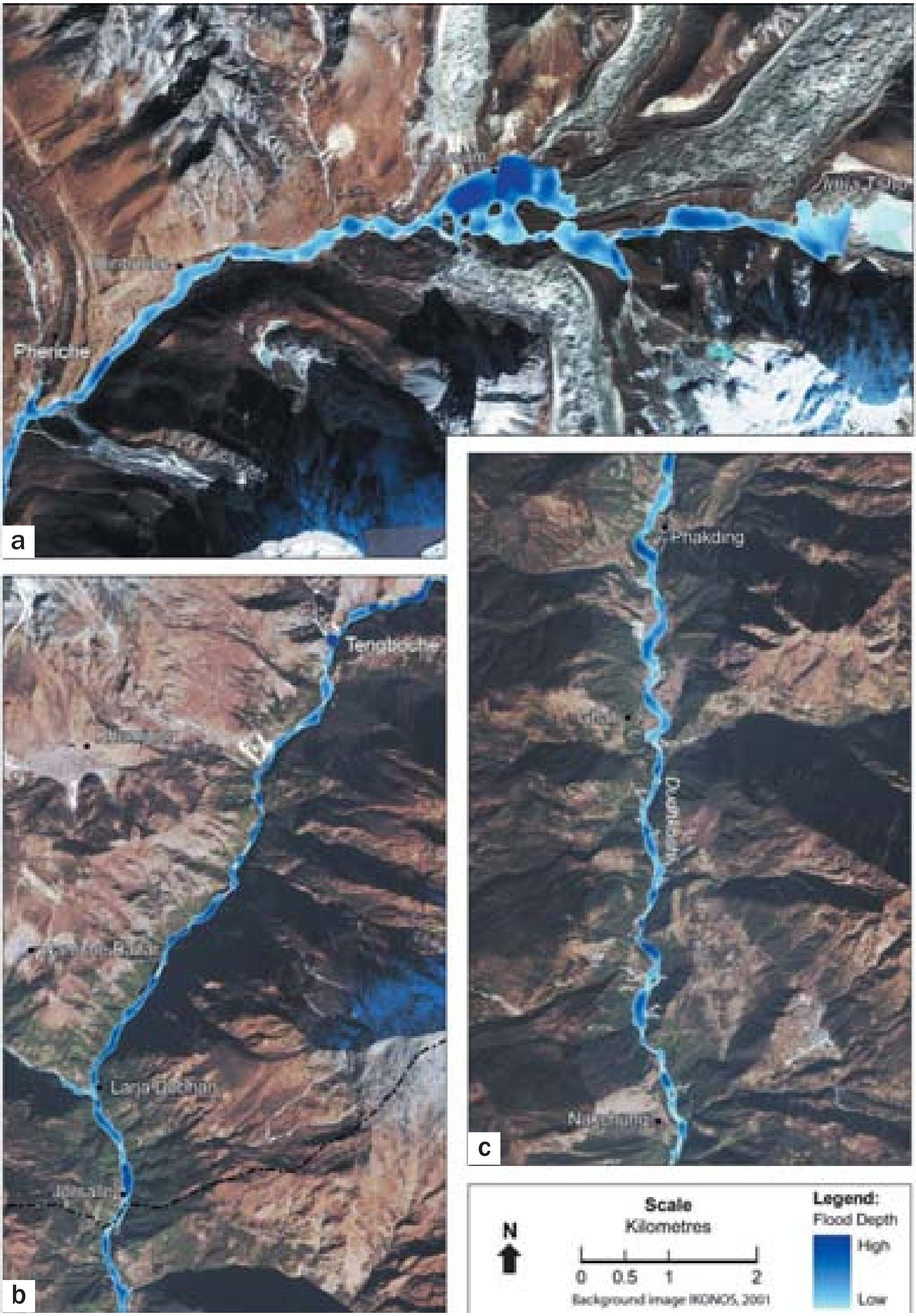


Figure 4.3: GLOF hazard in the Imja Khola, Bhote Koshi, and Dudh Koshi valleys obtained from NWS-BREACH. It depicts stretches between Imja Tsho and Pheriche (a), Tengboche and Jorsalle (b), and Phakding and Nakchung (c)

Table 4.4: **Valley cross-sections downstream of Lake Raphstreng Tso classified according to valley width**

Valley width (m)	Cross-section	Distance from lake outlet (km)	Location	Top width (m)	Avgerage Top width (m)
Wide (>500)	Lake	0.0	Lake		1030
	X_Section 1	2.6		1145	
	X_Section 2	9.9		1231	
	X_Section 10	84.9	Nanikha near the Punakha	839	
	X_Section 11	94.7	Yuesakha-Bewakha	903	
Medium (260 – 500)	X_Section 3	18.1		405	380
	X_Section 7	55.4	Giangkha-Chhuna	417	
	X_Section 9	74.7	Masepokto-Byaphu	413	
	X_Section 12	104.3	Hebesa- Dema	408	
	X_Section 13	114.3	Hebesa-Dema	359	
Narrow (<260)	X_Section 4	28.1		172	221
	X_Section 5	37.9		238	
	X_Section 6	46.1		218	
	X_Section 8	64.6	After the Ya Chhu River	255	

Table 4.5: **Lake surface area and storage volume of Lake Raphstreng Tso**

Altitude (m)	4360	4340	4320	4300	4280	4260	4240	4236
Surface area (sq. km)	1.018	0.821	0.667	0.391	0.119	0.023	0.003	0.000
Volume (million m^3)	20.353	16.412	13.331	7.829	2.324	0.412	0.0108	0
Volume used in model (million m^3)	20.353							

Dam breach model

A dam breach model developed by the National Weather Services (NWS-BREACH) was used to simulate the outburst of the moraine dammed Rapshtreng Tso glacial lake in order to simulate the GLOF hydrographs. The model requires inputs of field data; these data were gathered in part from topographical maps, from reports (Skuk et al. 2002; Yamada and Naito 2003) and from educated guesses of what might be reasonable, based upon extensive experience in the field. Important input parameters for the NWS-BREACH Model are given in Table 4.6

After the GLOF hydrograph was derived from the NWS-BREACH model, the nature of the flood propagation in the downstream areas was modelled hydrodynamically using the flood wave propagation model of National Weather Services (NWS-Flood Wave). The flow hydrograph derived from NWS-BREACH was used as the upstream boundary condition, and the downstream boundary condition was given as the discharge rating curve.

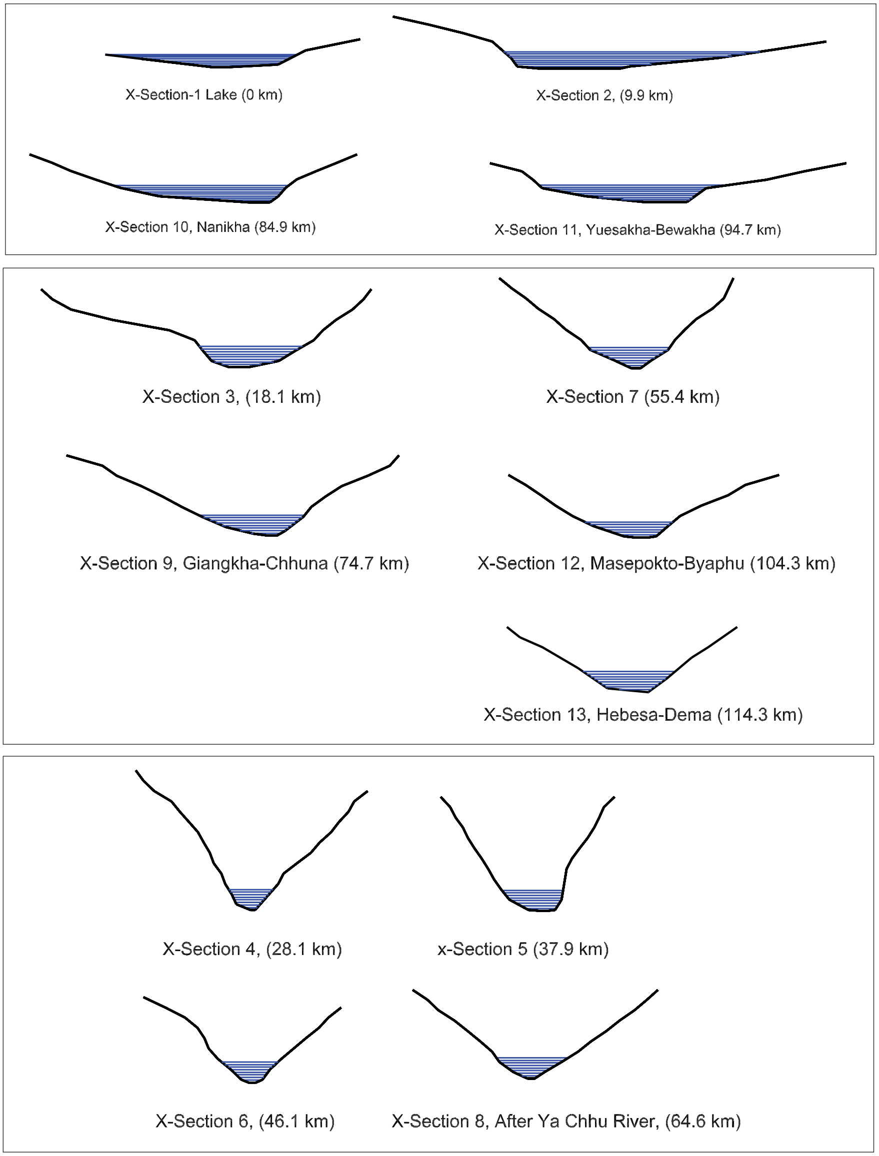


Figure 4.4: Typical cross-sections of the Pho Chu River valley

Results

The breach flow hydrograph is derived from the NWS-BREACH model, considering breach heights of 9 to 56m. The breach height of 56m is the maximum depth of breach corresponding to the characteristics of Lake Rapshtreng Tso as defined in the NWS-BREACH model. The breach peak flood simulated at the outlet for the maximum breach depth is 5450 m^3/s. The GLOF hydrographs for different breach heights from 9 to 56m show the magnitude of breach flow for different scenarios (Figure 4.5). The important output parameters derived from THE NWS-BREACH model are given in Table 4.7.

Table 4.6 **Parameters and input data for NWS-BREACH model for Lake Raphstreng Tso**

Parameter	Value
Lake surface area	1.018 km^2
Lake maximum depth	107m
Dam top elevation	4360m
Dam bottom elevation	4304.3m
Dam inside slope	1:06
Dam outside slope	1:08
Dam width	1.13 km
Dam length	1.94 km
d_{50}	1 mm
d_{90}	333.3 mm
d_{30}	0.1 mm
$d_{90/30}$	3333
Unit Weight	2100 kg m^{-3}
Porosity	0.41
Manning's n of outer core of dam	0.08
Internal Friction Angle (ø)	32
Cohesiveness	0
Source: Skuk et al. 2002; Yamada and Naito 2003	

A breach flow of 5450 m^3s^{-1} (for a maximum breach depth of 56m) is the maximum breach peak flow that can be propagated to downstream of the river valley in this model. The attenuation of this peak flow and the corresponding maximum flood depth along the river reaches is shown in Figures 4.6 and 4.7. The peak discharge at breach is 5450 m^3s^{-1} but decreases sharply to 3000 m^3s^{-1} within the first 10 km stretch, after which it remains stable for the next 30 km. About 40 km downstream the peak flood once again decreases sharply to a value of 500 m^3s^{-1} and becomes even lower over the next 50 km.

Figure 4.7 shows the peak flood depth along the rivers. Peak flood heights of 4m, 3m and 2m occur at 30 km, 40 km and 65 km downstream of the breach. However, the flood height at the Punakha settlement is estimated to be less than 1m due to rapid flood attenuation. The peak flow curves are irregular because of the large time and distance steps; as a result, some peaks might have been missed. Nevertheless, decreasing the size of either the time or the distance steps was not possible since this exceeded the storage capacity of the model.

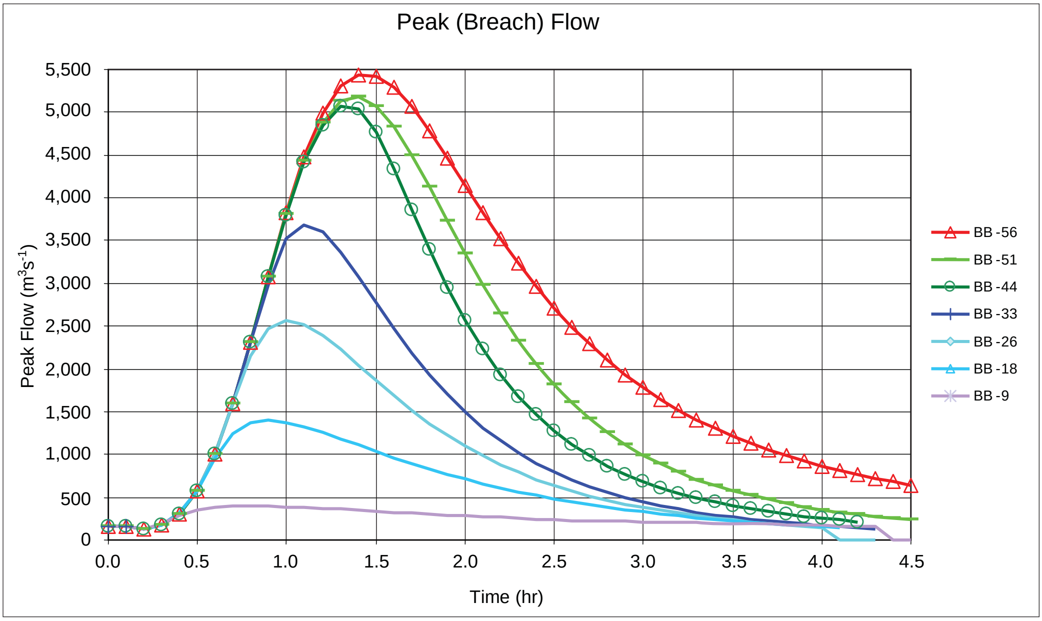


Figure 4.5: Lake Raphstreng Tso GLOF hydrograph obtained using NWS-BREACH

Table 4.7: **NWS-BREACH output for various breach heights (Bh=56m to Bh=9 m)**

Output summary	Bh=56	Bh=51	Bh=44	Bh=33	Bh=26	Bh=18	Bh=9
Max outflow (m^3s^{-1}) through breach	5450	5183	5084	3683	2571	1399	400
Time (hr) at which peak outflow occurs	1.44	1.38	1.32	1.10	1.00	0.91	0.78
Final depth (m) of breach	55.65	51.25	43.89	32.53	25.72	17.94	9.14
Top width (m) of breach at peak breach flow	93.93	90.09	86.91	67.96	56.17	41.88	23.82
Elevation (m) of top of dam	4360	4360	4360	4360	4360	4360	4360
Final elevation (m) of reservoir water surface	4313.6	4314.3	4321.3	4331.4	4338.4	4346.3	4354.7
Final elevation (m) of bottom of breach	4304.3	4308.7	4316.1	4327.4	4334.2	4342.0	4350.8
Side slope of breach (m/m) at peak breach flow	1.2	1.2	1.2	1.2	1.2	1.2	1.2
Bottom width (m) of breach at peak breach flow	2.6	2.6	2.6	2.6	2.6	2.6	2.6

Note: Bh indicates breach height

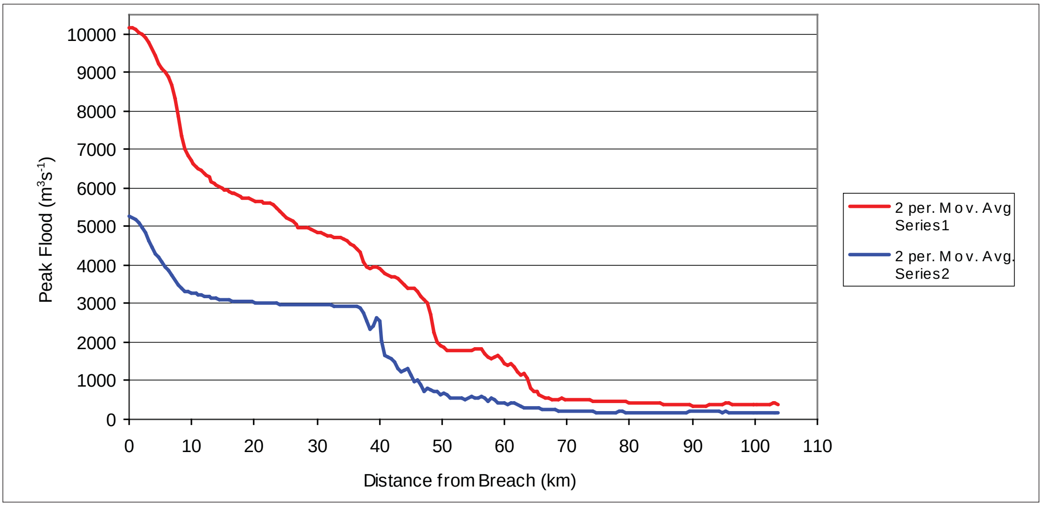


Figure 4.6: Peak flood attenuation scenarios in a worst-case flood, and a maximum breach for a possible Lake Raphstreng Tso GLOF in the Pho Chu valley

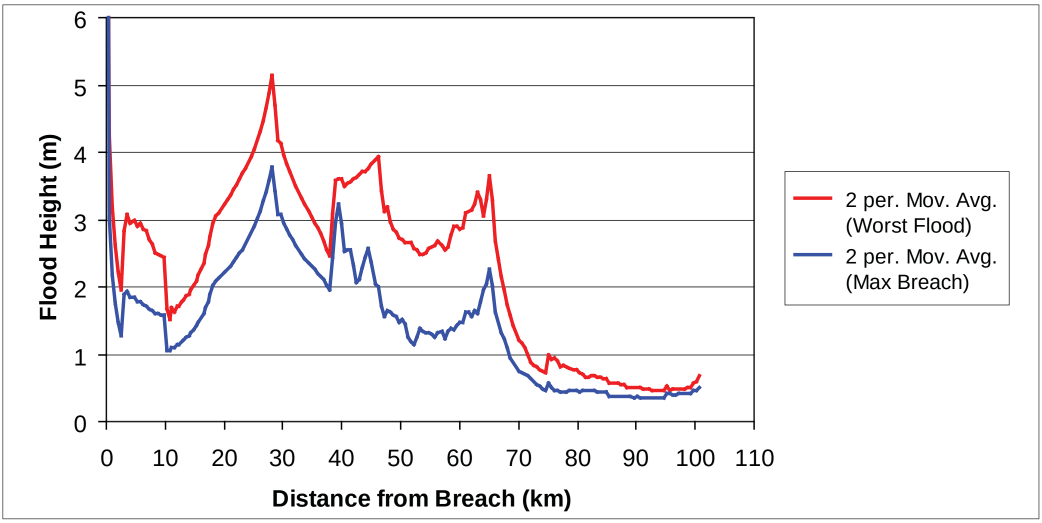


Figure 4.7: Peak flood height scenarios in a worst case flood and a maximum breach for possible Lake Raphstreng Tso GLOF in the Pho Chu sub-basin

The peak flood is rapidly attenuated downstream of the valley from the breach. In the wide portions of the valley (<10 km) the peak flood height is less than 2m, and beyond this it reduces further to less than 1m at distances of 85 to 95 km downstream. In medium width portions of the river valley (18.1 and 55.4 km) the peak flood height is 1-2m, reducing to less than 1m at 104 km. The maximum peak flood heights occur mostly in the narrower portions of the river valleys (at 28.1, 37.9, 46.1 and 64.6 kms) where distinctive peaks (2 to 4m in height) can be seen (Figure 4.7).

Scenario for worst-case peak flow

The NWS-BREACH model estimates a maximum breach height of 56m and peak breach flood of 5450 m^3s^{-1} based on the input parameters used. Some of these parameters had to be estimated, and could possibly have resulted in an underestimation of the peak breach flood. In light of the possible underestimation of the peak breach flood, it was thought prudent to double this number to 10,161 m^3s^{-1} in order to estimate a worst-case scenario for a catastrophic downstream flood. This worst-case peak flood scenario was used to evaluate the impacts of such tremendous magnitude (Figure 4.6 and 4.7). The peak flow (10,161 m^3s^{-1}) is sharply attenuated to 7000 m^3s^{-1} within the first 10 km of the lake outlet and continues to be more gradually attenuated to 2000 m^3s^{-1} within 50 km, finally diminishing to 500 m^3s^{-1} at 65 km and further downstream (Figure 4.8).

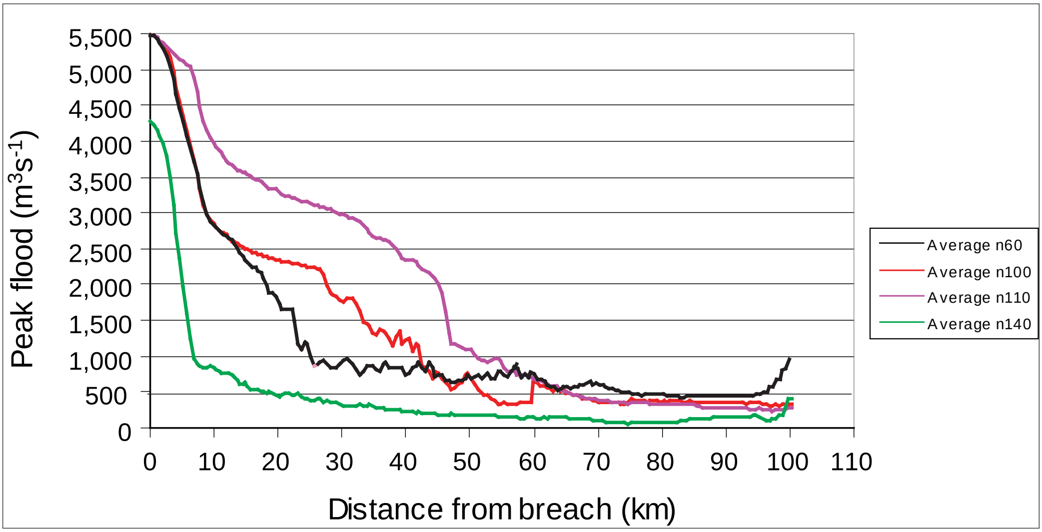


Figure 4.8: Variation of peak flow with Manning's 'n' in the Pho Chu sub-basin

The worst-case peak flood is also rapidly attenuated downstream of the valley from the breach. The wide valley (<10 km) has a peak flood height less than 3m, which further reduces to less than 1m between 85 and 95 km. The medium river valley (18.1 km, 55.4 km) has a peak flood height of less than 3m, which reduces to less than 2m at 104 km. The maximum peak flood heights appear mostly in the narrow river valleys (28.1 km, 37.9 km, 46.1 km, and 64.6 km) where distinctive peaks of 4-5m heights can be reached (Figure 4.7). Note that even in a worst-case flood, with a peak flood over 10,000 m^3s^{-1}, the GLOF is not likely to directly hit settlements such as Punakha.

Effect of variation of Manning's 'n'

The Manning's roughness coefficient 'n' determines the sub, super or critical flow condition that determines the flood height. The 'n' value was taken to be 0.08 for the lake outlet and 0.036 for all other reaches – both for the NWS-BREACH model and for the Flood Wave Model. Figure 4.8 shows how a variation in 'n' affects both the peak flood and the maximum flood height. When 'n' increases by 10 per cent, the breach outflow does not change but the downstream peak flood value continues to increase for up to 60 km beyond the lake outlet. When 'n' increases by 40 per cent, a significant decrease occurs in the breach outflow as well as in the downstream peak flood value throughout the downstream valley. When 'n' is decreased by 40 per cent, the breach outflow remains constant until 10 km from the lake outlet. The peak flood value decreases significantly between 10 and 50 km reach but remains almost the same after that.

Similarly, the flood height increases throughout the downstream when the 'n' value is increased by 10 per cent. However, both increasing and decreasing 'n' by 40 per cent have the same effect – the flood height decreases within 65 km from the lake outlet (Figure 4.9). Beyond 65 km from the lake outlet, changes in the value of 'n' have no significant effect.

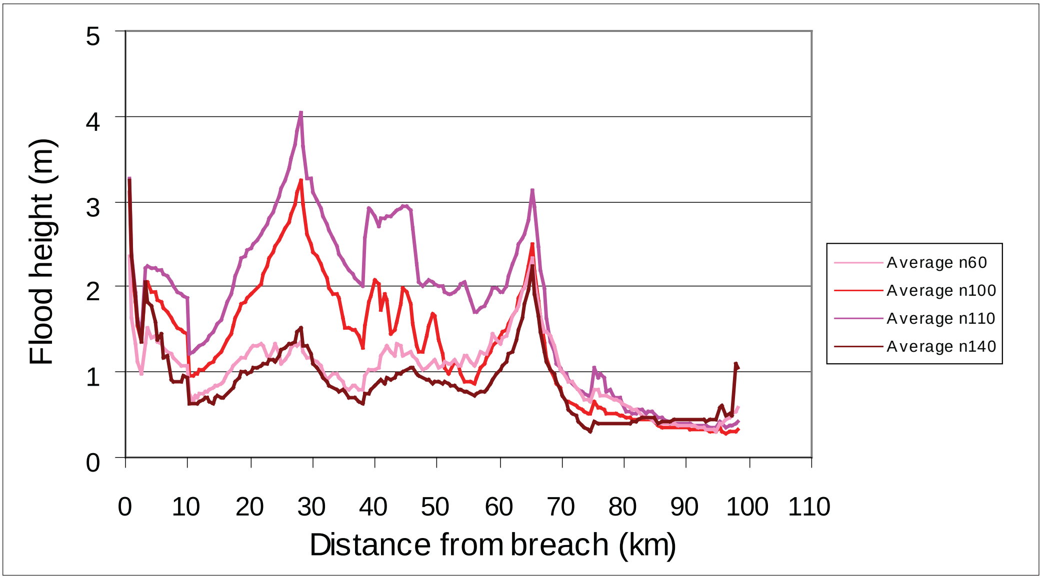


Figure 4.9: Variation of flood height with Manning's 'n' in the Pho Chu sub-basin

Limitations

While modelling can predict peak flood values, these results can be misleading because the impact of secondary processes can often be as devastating as the impacts of high floods. For example, the Lake Luggye Tso, which is adjacent to Lake Raphstreng Tso and similar to it in many ways, suffered a GLOF event in 1994. This model might have predicted that settlements downstream of the breach, where the peak flood value was only about a meter or so, should have been safe. However, the model cannot capture the extent of erosion processes and downstream sedimentation, which are highly dependent on local conditions such as gradient, curvature of the river, valley width and river depth, geomorphology, and so on. What happened on site was that erosion and sedimentation of the river valley continued very far downstream from the breach (Chapter 2, Figure 2.9). The Punakha settlement (containing the religious shrine of Punakha Dzong), which lies about 85 km downstream, was seriously devasted, not by the flood itself but by these secondary events.

In this study, the topographical information (cross sections and longitudinal profile of the stream) were derived from a 1 inch to 1 mile topographical map; other geo-technical parameters were either taken from reports or were based on suitable assumptions. The results of the modelling based on these parameters are preliminary and subject to change as more field-based data becomes available. To run successfully, the model requires that the time and distance steps used be 'small' and that many cross sections be used at the transition of very narrow and wide sections. Limitation in storage capacity arises when small time steps are used but larger time steps can not capture peaks and also prevent the model from converging.

GLOF hazard maps, based on the hydrology and morphology of the river, and which integrate the geomorphology of both of the river and of the vicinity, should be made available to people planning development work in the Pho Chu sub-basin. The possibility of upstream GLOF events must be taken into consideration at the design stage to minimise damage. Vulnerability maps need to be prepared to help anticipate the impacts of GLOFs so that mitigation work can be undertaken.

Glacial Lake Outburst Floods and Associated Hazards in Nepal

Chapter 5

Terrain Classification, Hazard and Vulnerability Assessment of the Imja and Dudh Koshi Valleys in Nepal[1]

The Khumbu region of Nepal has experienced three GLOF events in the recent past: Nare (1977), Dig Tsho (1985), and Tam Pokhari (1998). Lake Imja Tsho in this same area is noted to be growing at a high rate (Chapter 3); it has a storage capacity of about 36 million cubic metres and is situated at an altitude of 5020m. The rapid expansion of this lake and its extensive storage capacity (more than six times that of the Dig Tsho, which burst in 1985) make it the most hazardous lake in the Khumbu region of the Nepal Himalaya. As seen from the simulations (Chapter 4) the consequences of a Lake Imja Tsho GLOF would be devastating to the downstream areas. The damage would be particulary devastating to the human population since the Khumbu region is one of Nepal's most densely populated high-mountain areas, and its proximity to Mt. Everest makes it one of the most popular tourist destinations in the country. A GLOF event at Lake Imja Tsho would jeopardise populated valleys, tourist areas, trails, and bridges. The tremendous volume of water already retained behind the moraine dam at Lake Imja Tsho requires that it be closely monitored. The terrain classification work discussed in this chapter is essential to support monitoring, evaluation and mitigation work, all of which will help to reduce the GLOF risk.

The most recent GLOF event in the Khumbu region was the Dig Tsho GLOF of 1985. This GLOF had an enormous impact on the downstream areas it shares with Lake Imja Tsho. Impacts like bank erosion and landslides are visible even today in the Langmoche, Bhote Koshi, and lower Dudh Koshi valleys. All indications are that, for several reasons, the impacts of a Lake Imja Tsho GLOF on the river valley below would be much more severe than those resulting from the Dig Tsho GLOF. First, the lake retains about six times more water. Second, lateral erosion in the downstream valleys remains active after the most recent GLOF event, the upper Imja and upper Dudh Koshi valleys already face severe erosion and sedimentation problems, and slope instability has been a longstanding problem in these valleys. Third, old and new lateral erosion could occur over a larger area and at steeper slopes along the river valleys.

GLOFs often set in motion a complex set of catastrophic events including floods, sediment transport, and large debris flow, none of which can be accurately predicted or foreseen; nevertheless, terrain units (TU) can be a good indicator of the magnitude of what might transpire. The GLOF hazard map along the Imja and Dudh Koshi valleys was updated using the terrain unit responses from the 1985 GLOF. This map can be used as a tool to help create awareness among both local people and tourists about the real dangers that GLOFs pose to human life and infrastructure. GLOF hazard awareness is also needed for any further

1 Contributed by S.R. Bajracharya, P.R. Maskey, and S.P. Joshi

infrastructure development in the area. Construction of many suspension bridges in the downstream valleys after the Dig Tsho GLOF benefited from lessons learned from the catastrophe; they were built at higher elevations to minimise the impact that another flood might have on their infrastructure. However, the bridge at Hilajun (at the Langmoche – Bhote Koshi confluence) in the Dig Tsho basin is located on the flood plain, and remains vulnerable to GLOFs. Although the Dig Tsho GLOF flooded houses located downstream from Phakding village, the number of houses in this flood-prone area is still increasing. Houses located on lower terraces (mostly in the Benkar, Phakding, and other low-lying areas) are at high risk of both flooding and lateral erosion.

Terrain classification

For the purposes of this study, the riverbed slopes were classified (Table 5.1) and the GLOF hazard areas downstream of Lake Imja Tsho divided as shown in Figure 5.1 and summarised in the following box. Past experience with GLOF hazards suggests that river reaches can be categorised into different terrain units (Tables 5.2 and Figures 5.2 to 5.5) to help evaluate the risk from a possible GLOF. The impact that the past Dig Tsho GLOF had on the river valley and the field knowledge gained from that experience were incorporated into the classification of the terrain units. Five terrain units were defined based on the characteristic features of their river reaches: river gradient, valley width, height of the terraces, river curvature, and settlements. The definitions are given in the box. These terrain units will be used as part of the information needed for hazard assessment of the Imja and Dudh Koshi valleys.

The entire Imja Khola riverbed is mostly classed as either S1 or S2; the maximum gradient is 0.126 and the minimum gradient is 0.028. The average gradient of the river bed is 0.075, and on average is classed as S2. The Langmoche Khola (with the exception of its lower reaches) and the Bhote Koshi have gradients similar to the Imja Khola. The lower reaches of the Langmoche are slightly less steep than the upper reaches and can be classed as S2 and S3. The gradient of the lower Dudh Koshi are classed as S2 and S3 and have a maximum gradient of 0.069 and a minimum gradient of 0.017. The average gradient of the lower Dudh Koshi is 0.041 and is classed as S3. The Langmoche river valley and the Imja Khola river valley have similar gradients and share a common river section beyond Larja Dobhan. Using information from the 1985 Dig Tsho GLOF as a guide, and comparing the river morphologies (gradient, curvature, width of the valley, height of the terraces, and others) one could predict that if an Imja GLOF occured, it would have an impact at least six times greater than the Dig GLOF of 1985.

Table 5.1: **Classification of riverbed slopes of Imja, Langmoche, Bhote Koshi and Dudh Koshi**

Valley	Slope		
	Maximum	Minimum	Average
Imja (Lake Imja Tsho to Dudh Koshi confluence	0.126	0.028	0.075
Upper Dudh Koshi (Imja-Dudh Koshi confl. to Larja Dobhan)	0.096	0.043	0.075
Lower Dudh Koshi (Larja Dobhan to downstream)	0.070	0.018	0.041
Langmoche (Dig Tsho to Hilajun)	0.112	0.057	0.084
Bhote Koshi (Hilajun to Larja Dobhan)	0.107	0.072	0.086

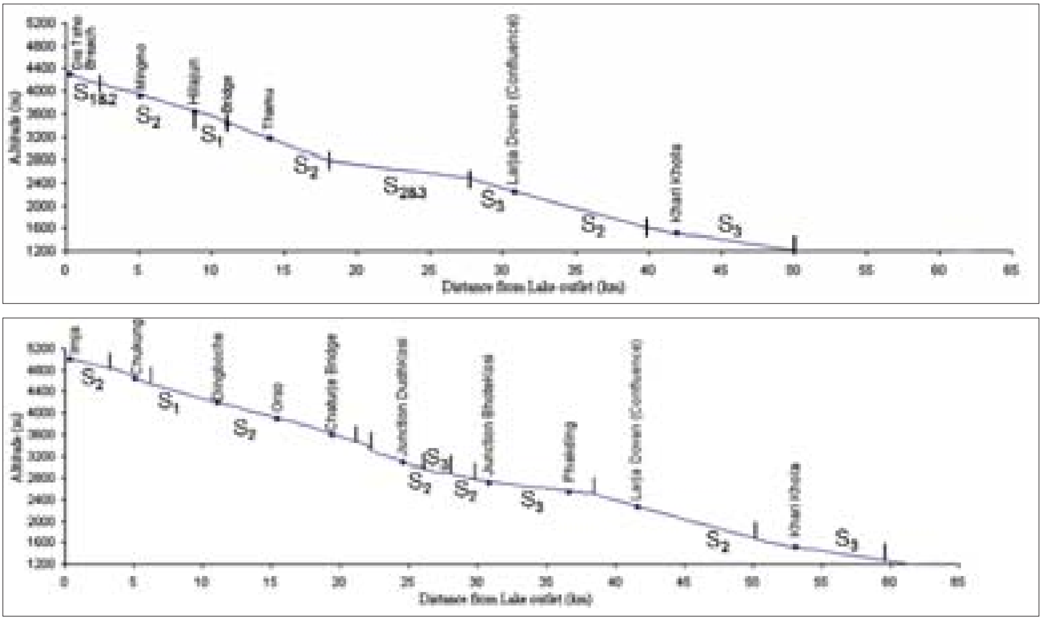


Figure 5.1: Slope profile of the Langmoche (top) and Imja (bottom) Khola down to Khari Khola confluence near Lukla village

Terrain Units in Langmoche, Bhote Koshi, Imja and Dudh Koshi

Segments	Valley
I-1 to I-11	Imja Valley from Imja outlet to the Dudh Koshi Confluence
I-11 to DI-1	Upper Dudh Koshi valley from the Imja – Dudh Koshi confluence near Tengboche to Larja Dovan
DI-downstream	Lower Dudh Koshi from Larja Dovan to Lukla and areas further downstream
D-1 to D-4	Langmoche valley from Lake Dig Tsho to the Bhote Koshi confluence
D-4 to DI-1	Bhote Koshi valley from the confluence to Larja Dovan

Terraces are classified according to height

- **lower** (<5m above the riverbed)
- **middle** (5 >10m above the riverbed)
- **upper** (>10m from the riverbed)

River valley reaches are classified according to the width of the river valley

- **narrow** <50m wide
- **moderate** 50 >100m wide
- **wide** >100m wide.

River bed gradients (slope): the reach of the river from Dig Tsho and Lake Imja Tsho to Lukla village is classified as

- **S1** ≥ 0.10: very steep
- 0.05 < **S2** <0.1: steep
- 0.05 ≤ **S3**: moderately steep

Terrain units are classified as:

- **TU1**: Narrow valley with steep river gradient and breach fan
- **TU2**: Upper terrace with narrow valley
- **TU3**: Middle upper terrace with moderately wide valley
- **TU4**: Lower terrace with wide valley
- **TU5**: Upper terrace with wide valley

The maximum gradient (0.126) is found in the Imja valley and the minimum gradient (0.018) in the lower Dudh Koshi valley (Figure 5.2 and Table 5.1).

Table 5.2: **Terrain classification of the Langmoche, Bhote Koshi, Imja, and Dudh Koshi valleys (up to Ghat village)**

Terrain Unit	Riverbed materials	Characteristic features	Erosion / Sedimentation from GLOF	Section	
				Langmoche Khola and downstream	Imja Khola and downstream
TU1: Narrow steep river with breach fan	*Straight reach:* very big boulders >1 m dominant, huge amount of sediment deposit	Very steep river (S1), V-shaped side slopes at outlet, rapids and falls, severe bed and bank erosion	Severe bed abrasion, bank widening and erosion, huge sedimentation of large boulders >1 m dominant	Outlet, breach, immediate downstream valley	Imja outlet, immediate downstream valley
TU2: Upper terrace with narrow valley	*Narrow:* 0.5m dominant, 1-2m scattered	Very steep river (S1), rapids, jump, extensive landslides upstream and downstream of narrow section and bends	Severe lateral erosion extending to 10m height, about 200 m upstream and downstream, upstream sedimentation, downstream erosion of bed and bank	Thame gorge	Imja constriction, Milingo gorge
		Steep (S2), rapids, jumps, and sharp bends within a relatively wide river valley	Severe erosion of bends, deposition at bed	Bhote Koshi-Langmoche and Bhote Koshi- Dudh Koshi confluence	Bhote Koshi-Dudh Koshi and Tsuro confluence
		Steep (S2), rapids, jumps, narrow, incised bed rock, highly dissected by channels, inaccessible river valley	Severe lateral and bed erosion at narrow sections and sharp bends, location for temporary damming	Thamu- Larja Dovan	Milingo Bridge – Larja Dovan, Syomare
			Severe lateral and bed erosions at narrow sections and sharp bends; settlements at upper terrace affected by landslide	Thado Koshi, Nachipan, Senma, Chheplun, Tate, Muse, Rondinma, Lukla, Chaurikharka,	
TU3: Middle o upper terrace with moderately wide valley	*Bends:* sedimentation <0.5m dominant, 1m few	Moderately steep (S3), short sharp bends, rapids, falls, over-topping of lower terraces, reactivation of old slope instability	Over-topping of banks, severe lateral erosion of shorter length and medium height, series of lateral erosion on outer bends	Ghat, Chutawa, Chermading, Phakding, Benkar Tawa, Jorsalle	
TU4: Lower terrace with wide valley	*Bends:* sedimentation with <0.3m dominant, 0.5-2m significant	Steep (S2), rapids, jumps, bed bars, meander, moderate bed slope, wide valley	Severe lateral erosion of low height and short length at outer sharp bends, lateral erosions of low heights extending higher level at steep slopes.	Langmoche	Pipre Goth, Chhukung (next valley)
	Straight reach: <0.3m dominant, 1-2m scattered	Steep (S2), rapids, meander, channel bars, wide valley	Bed abrasion, widening and deposition of boulders, bank erosion to lower terraces extending to upper terraces on weak geological locations	Langmoche valley Hilajun, Thamo Teng	Imja valley
TU5: Upper terrace with wide valley	*Bends:* <0.3m dominant, 0.5-1m significant 1-2m scattered	Steep (S2), braided, channel bars, meander	Lateral erosion at lower terrace level, sedimentation of river valley with finer materials	Chamuwa, Kamthuwa, Mingmo	Chamuwa, Tsuro, Orsho, Pangboche, Dingboche
	Straight reach: <0.5 m dominant, 0.5-1 m significant, 1-2m scattered	Moderately steep (S3), meander, channel bars	Settlements not affected by flood, lateral erosion at bends at low level, sedimentation of fine materials	Monjo, Thamu	Monjo, Tsuro

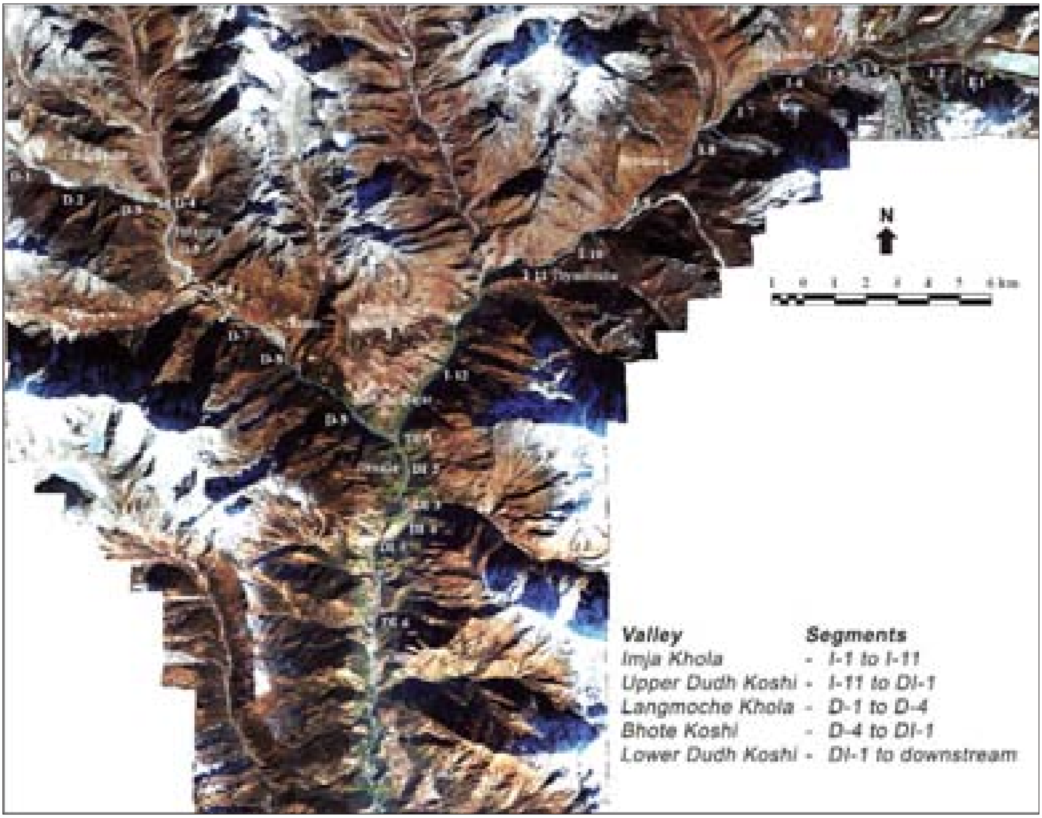


Figure 5.2: Homogeneous geomorphic segments used to classify Langmoche, Bhote Koshi, Imja, and Dudh Koshi valleys into terrain units, as shown in Figures 5.3 - 5.5, base image IKONOS

Figure 5.3: Terrain units (see Table 5.2) from Lake Imja Tsho to Namche Bazar (Larja Dobhan)

Figure 5.4: Terrain units (see Table 5.2) along the Langmoche valley and Bhote Koshi valley from Lake Dig Tsho to Namche Bazar (Larja Dobhan)

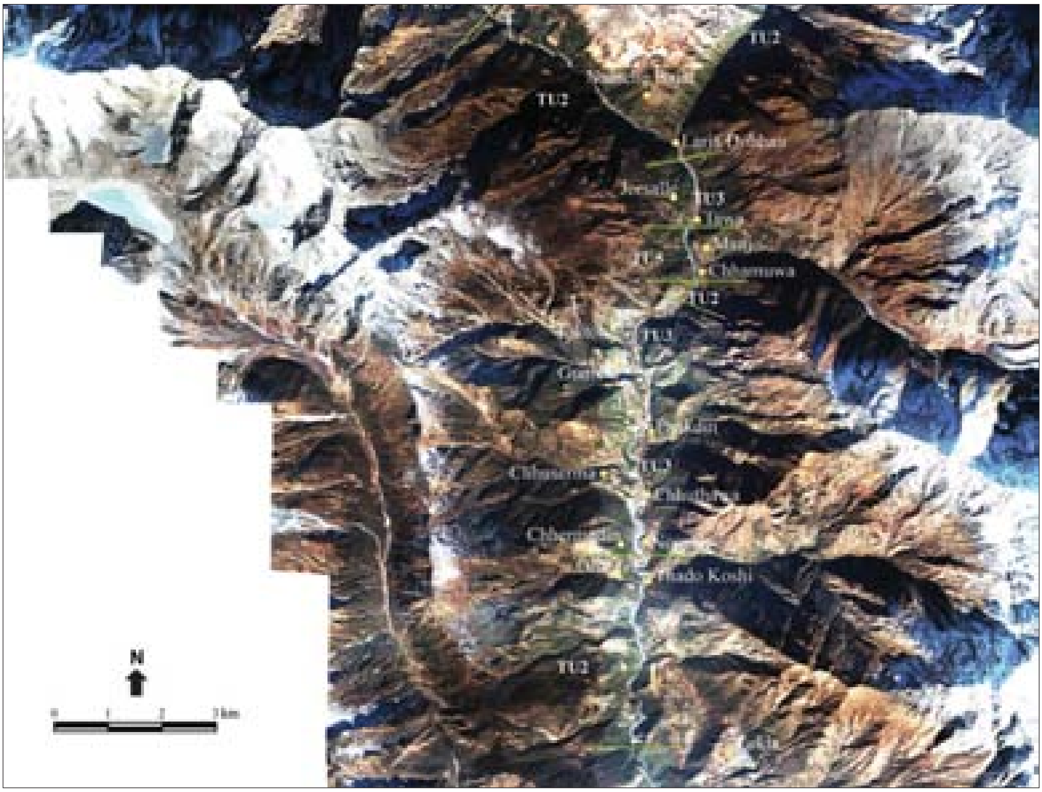


Figure 5.5: Terrain units (see Table 5.2) from Larja Dobhan to Lukla in the Dudh Koshi river valley

Terrain Unit TU1: Narrow valley with steep river gradient and breach fan

The characteristics of TU1 are:

- bed scour,
- bank erosion and widening,
- sedimentation of large boulders, and
- destruction of infrastructure.

TU1a – Dig Tsho (lake outlet, breach section, and downstream; Langmoche – Bhote Koshi valley)

The Dig Tsho GLOF of 1985 deposited a large amount of sediment, ranging in size from big boulders to silt, on the immediate downstream valley (Figure 5.6). The sediment gradually diminishes in size the further it is from the lake outlet. The valley is characterised by a large amount of sediment and many huge boulders. The wide valley, with the debris fan resulting from the GLOF, is shown in Figure 5.7.

GLOF events also cause riverbank erosion. Past GLOFs of Nare, Dig Tsho, and Tam Pokhari in the Dudh Koshi valley have caused extensive erosion of riverbanks and have deposited massive breach fans in their respective river valleys.

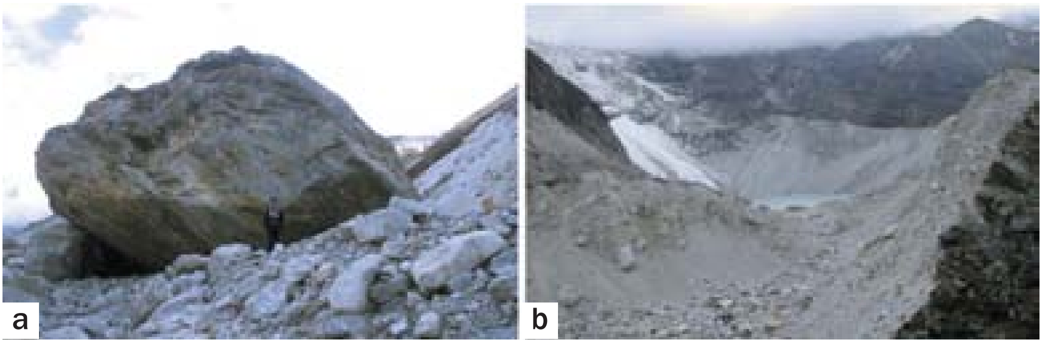


Figure 5.6: Lake Dig Tsho, breached channel and GLOF fan deposits: a) A big boulder resting on debris in the breached valley; b) Lake and breached section

TU1b – Lake Imja Tsho (lake outlet and immediate downstream Imja valley)

Lake Imja Tsho is dammed by a thick, large area of end moraine and exhibits hummocky terrain near the outlet; these are indications that an Imja GLOF may carry with it a very large amount of debris, predictably more so than any other previously recorded GLOF in Nepal (Figure 5.8).

Figure 5.7: Sediments deposited downstream of Dig Tsho

The outlet of Lake Imja Tsho drains through a sloping moraine that opens up into a wide valley immediately after the moraine dam (Figure 5.9). In the case of a GLOF, the wide valley below will experience extensive bed and bank erosion and large amounts of debris will be deposited.

Before the GLOF enters the narrow valley constriction near Pipre Goth, it first traverses a very wide valley where the sediments will most probably be sorted. The bigger size boulders are expected to be deposited nearer the outlet while finer ones will accumulate further downstream. By the time the flow reaches the constriction (4.5 km downstream) the sediment is expected to be quite small (Figure 5.10).

Figure 5.8: Supraglacial lakes and hummocky terrain around Lake Imja Tsho

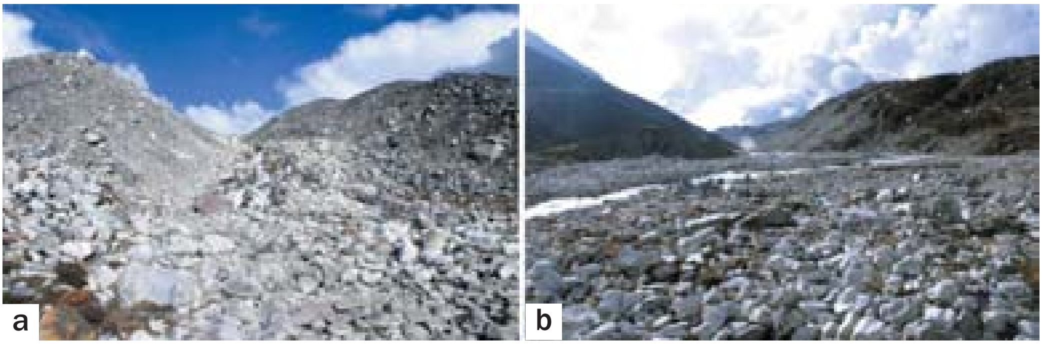


Figure 5.9: Cobble-size sediments deposited at the Lake Imja Tsho outlet (a) and downstream (b)

Figure 5.10: The downstream view of the wide Imja valley before reaching the constriction near Pipre Goth

Terrain Unit TU2: Upper terrace with narrow valley

The characteristics of TU2 are:

- severe abrasion of bed and banks at narrow sections,
- severe lateral erosion upstream and downstream of bends at narrow section extending to terraces of heights of 10m and more,
- deposition of sediment at river bed upstream but scour downstream of narrow section, and
- sedimentation at middle wide river confluence.

TU2a – Dig Tsho (Thame gorge, Bhote Koshi – Langmoche and Bhote Koshi – Dudh Koshi confluence, and Thamu – Larja Dovan)

The terrain unit TU2a consists of upper terraces, narrow valleys and/or sharp bends; it is characterised by lateral erosion at bends upstream and downstream of the river reach (approx. 400m). Bed erosion is prominent at narrow sections and/or sharp bends. This section is very narrow when compared to the adjoining upstream and downstream sections. This narrow section of the river reach acts as a flood control structure during peak GLOF flow and helps retain the flood and debris upstream. This type of section is found at the Thame gorge, Bhote Koshi–Langmoche confluence, Bhote Koshi–Dudh Koshi confluence and Thamu–Larja Dovan.

The narrow sections would experience a high velocity of flow, a series of falls and rapids, severe abrasion of rock surfaces and both downstream bed and lateral erosion. Examples of this type of terrain unit are the Thame and Milingo gorges. Areas both upstream and downstream of these narrow sections would be affected by lateral erosion that would extend some 10m or more on both sides of the river valley. The Thame gorge is about 15m wide and is incised in the bedrock. It contains a series of falls. The bedrock has been extensively abraded in the narrow section. Both the upstream and downstream portions of this reach have lateral erosion of both banks. The erosion at the steep slopes is still active on both banks (Figure 5.11). The Thyanmoche (Thame Teng) located upstream of this narrow section has bank erosion at several points and sedimentation is seen on the river bed. The bed material at Thame Teng is smaller than at the lake-breach area.

Both the Langmoche Khola and Bhote Koshi rivers have sharp bends upstream of the confluence. Lateral erosion has occurred at the bends of both rivers. The sediment scoured from these sections is deposited at the confluence (Figures 5.12 to 5.14). Erosion of the

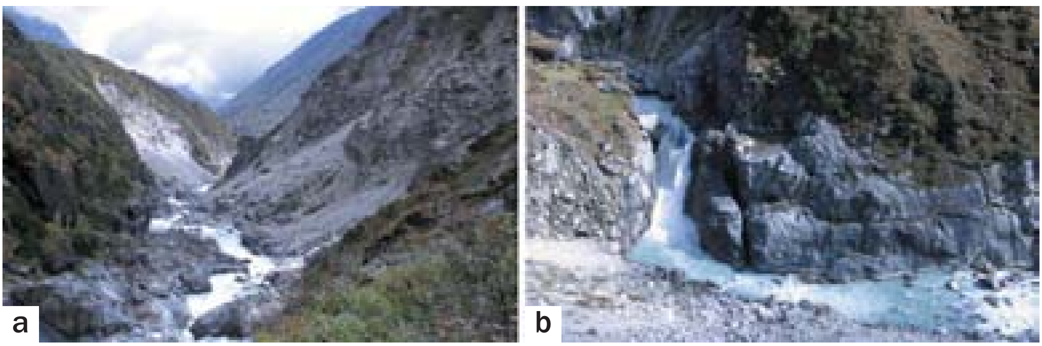


Figure 5.11: Narrows in the Langmoche valley: a) downstream view of both banks with landslides; b) upstream view of the Thame gorge

Figure 5.12: Erosion and sedimentation at the Langmoche (background) and Bhote Koshi (right and foreground) confluence. View upstream

Figure 5.13: Erosion and sedimentation observed at the confluence of the Langmoche Khola and Bhote Koshi. View upstream

Figure 5.14: Bank erosion at the Bhote Koshi–Langmoche confluence

bedrock on the left bank and the palaeo-moraine on right bank is observed. The erosion on the palaeo-moraine extends from the riverbank to the upper river terraces. Similarly, both banks of the Langmoche Khola, which consist of old moraine sediments, have experienced extensive lateral erosion. The lateral erosion extends from the valley floor to the upper terraces.

The river section between Thamu and Larja Dovan passes through a narrow valley. This river section is incised in the bedrock and vegetation cover on both valley slopes (Figures 5.15 to 5.17). The tributaries to this section are also steep, with highly dissected valleys, and can transport larger boulders to the Bhote Koshi. These local streams deposit large boulders and sediment. This type of sediment deposit can be observed in the Larja Dovan, Jorsalle, Tawa, Benkar, and Ghat villages. The lower valley sections are steeper and are covered by thick forest. Settlements are situated only on the upper terraces where the GLOF should have no effect at all.

Figure 5.15: Narrows at Phunki Thanga. View downstream

Figure 5.16: A boulder caught in the narrows between Latho Goth and Larja Dovan. View downstream

Figure 5.17: The deep valley of Lower Dudh Koshi near Larja Dovan. View downstream

Both the Bhote Koshi and Dudh Koshi flow through a narrow valley composed of bedrock near the confluence. The concave bend of the Dudh Koshi records bank erosion while the convex side contains many big boulders (larger than 50 cm) presumably deposited during the Dig Tsho GLOF (Figure 5.18). Due to the deposits of boulders, the level of the right bank is higher than the left bank (Figures 5.19 and 5.20).

Figure 5.18: Erosion and sedimentation at the confluence of the Dudh Koshi (foreground) and Bhote Koshi coming from the left (background) looking upstream of the Bhote Koshi

Figure 5.19: Downstream view of the Dudh Koshi River from Larja Dovan

Figure 5.20: The Bhote Koshi (right) and Dudh Koshi (left) at Larja Dovan looking downstream

TU2b – Lake Imja Tsho (Pipre Goth [Imja Constriction], Milingo gorge, Tsuro confluence, Milingo Bridge – Larja Dovan and Syomare)

This type of terrain unit includes narrow sections in the Imja valley at Pipre Goth (Imja Constriction), Milingo gorge, Tsuro confluence, and Milingo Bridge–Larja Dovan section, and in the lower Dudh Koshi valley at Thado Koshi, Nachipan, Senma, Chheplun, Tate, Muse, Rondinma, Lukla, and Chaurikharka.

The section upstream of the Milingo Bridge is characterised by narrow sections passing through bedrock and by a series of falls similar to the Thame Gorge. The sections both upstream and downstream of the Milingo Gorge have severe bank erosion. The trekking trail on the left bank is affected by river scouring resulting in active landslides (Figure 5.21).

During a GLOF, the Milingo gorge may suffer from extreme bed and lateral erosion similar to the Thame gorge. The lateral erosion both upstream and downstream of the Milingo george will extend to the upper terraces at steeper slopes. Similarities between the narrows of Milingo and Thame are shown in Figures 5.21 and 5.22. A total washout of the trekking trail and a reactivation of massive landslides are inevitable.

Immediately downstream from Lake Imja Tsho, the river valley is very wide, gradually reducing to a narrow section called the Imja constriction. The constriction was caused primarily by the convergence of two lateral moraines. There is another narrow valley below Milingo. The wide valley narrows at the sharp bends of the river section. A possible GLOF impact on the Imja

Figure 5.21: Landslides on the narrows of Milingo, view upstream

Figure 5.22: Downstream view of the narrows of Thame with landslides on the right bank

constriction can be inferred from the scenario at the Thame gorge during the 1985 GLOF, and extreme bed and lateral erosion is expected.

The section of the Imja River that extends from Latho Goth to Larja Dovan has characteristics similar to those at Thamu–Larja Dovan. This reach is also characterised by a narrow river valley with tributaries of steep gradient and a dissected topography with dense vegetation (Figure 5.23). Settlements are located only on the upper valley terraces. Figure 5.16 shows a boulder caught in the narrows where temporary damming during GLOF is possible.

The Imja River has a sharp bend downstream of the Imja constriction at Pipre. The sharp bend can cause severe bank erosion at the outer bend similar to that at the Hilajun outer bend. A wide downstream valley at Chhukung would receive a deposit of dominant boulders larger than 50 cm as occurred at Hilajun and Thame Teng following the Dig Tsho GLOF. Extreme lateral erosion with many landslides on the banks of lower terraces would probably occur downstream of the confluence.

In the areas upstream of the Tsuro confluence is a wide valley. The debris seen on the left bank derive mainly from the Nare GLOF (Figure 5.24). Before reaching the confluence, the Imja River passes through a narrow valley made up of the Tsuro glacial deposits. The area at the confluence of the rivers from the Khumbu Glacier and the Imja River (near Pheriche village) is a wide valley but the river narrows near the Tsuro confluence (Figures 5.25 and 5.26). Upstream of the confluence (towards the Imja River) are several bends where extensive erosion is possible; this area consists of the palaeo-moraine of the Tsuro glacier. These sediments might be transported long distances, possibly even beyond Orsho. Such a process is seen at the Langmoche–Bhote Koshi confluence and the Bhote Koshi–Dudh Koshi confluence (which experienced the Dig Tsho GLOF).

Figure 5.23: The downstream view of the Dudh Koshi River from the Milingo bridge, showing extensive erosion

Figure 5.24: A wide valley upstream of the Tsuro confluence. The debris on the left bank derives from the 1977 Nare GLOF

Figure 5.25: Upstream view of the Imja valley from the Tsuro confluence

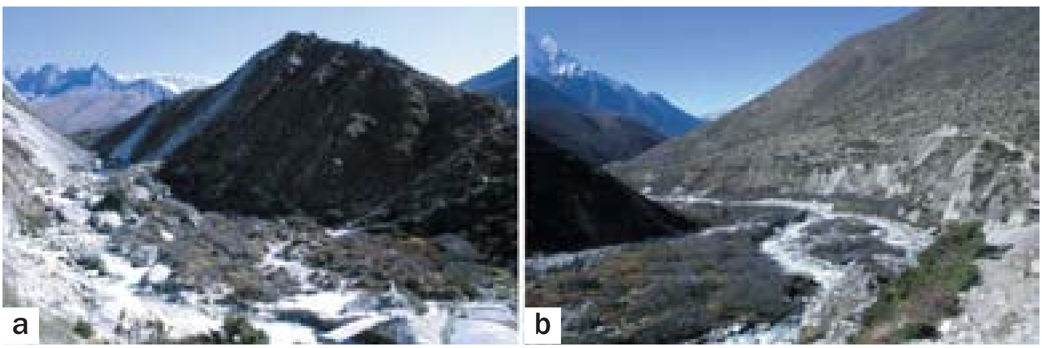


Figure 5.26: Situation near the Tsuro confluence: a) Upstream view to Pheriche, b) downstream view to the Imja valley

TU2c – Lower Dudh Koshi (Thado Koshi, Nachipan, Senma, Chheplun, Tate, Muse, Rondinma, Lukla, and Chaurikharka)

Narrow valley sections are also observed in the lower Dudh Koshi valley at Thado Koshi, Nachipan, Senma, Chheplun, Tate, Muse, Rondinma, Lukla, and Chaurikharka. In these areas, extensive erosion is expected to occur and large amounts of sediment may be deposited on the adjoining sections.

Terrain Unit 3: Middle upper terraces with moderately wide valleys

The characteristics of TU3 are:

- moderately wide river valleys with settlements located at middle to upper terraces,
- many short and sharp bends both upstream and downstream of the settlements,
- direct impact and overtopping of lower terraces (<5m) by flood,
- lateral erosion of banks mostly to lower terraces (<5m), occasional progression of lateral erosion to upper terraces at points where the geology is weak, and
- sedimentation of riverbeds by boulders >0.5m with significant boulders of >1m due to local erosion and sedimentation process both upstream and downstream.

TU3 – Lower Dudh Koshi (Jorsalle, Tawa, Benkar, Phakding, Dukdinma, Chermading, Chhuthwa, Nurnin, Ghat, and Nakchun)

The river reach in this terrain unit has moderate width but is characterised by a series of sharp bends at frequent intervals. The river gradients are moderately steep with a number of rapids and falls. This type of terrain unit is mainly confined to Jorsalle, Tawa, Benkar, Phakding, Dukdinma, Chermadin, Chutawa, Nurnin, Ghat, and Nakchun (Figure 5.27). The river banks are unstable where lateral erosion is dominant. The stable and the critical slopes are mostly covered by vegetation. Extensive lateral erosion is caused by the presence of a series of sharp bends at short intervals. Most of the alluvial fans result from local tributaries. With few exceptions, these areas are distant from Lake Imja Tsho. Here sedimentation of cobble size boulders and overtopping of the lower terrace with settlements is expected.

Most of the bridges, agricultural land, and settlements of Ghat, Nurnin, Chutawa, Chermadin, Dukdinma, Phakding, and Benkar lie on lower terraces that could be overtopped by debris and flood from a GLOF at Lake Imja Tsho (Figure 5.27). The cultivated land and settlements of Chuthawa, Chermading, Phakding, and Benkar are directly at high risk from a GLOF event and could also suffer damage from secondary events such as landslides on medium to upper terraces. Since these areas were previously affected by the Dig Tsho GLOF, the likelihood of their being affected by a GLOF event at Lake Imja Tsho is high.

Infrastructure, such as bridges destroyed in the 1985 GLOF, was rebuilt at higher elevations and is now nominally above flood level. However, commercial structures at Phakding, Benkar, and Chutawa such as hotels and lodges are typically built on lower terraces that are prone to flood hazards. These areas are highly vulnerable to hits from primary GLOFs and are not immune to secondary hits from lateral erosion extending to the upper terraces. The impact of the 1985 Dig Tsho GLOF is still visible in the form of old erosion scars and unstable zones with sparse vegetation.

Figure 5.27: Vulnerable river sections near main villages (between Larja dovan and Ghat) in the Dudh Koshi valley: a) Chutawa village and surroundings; b) Lateral erosion at Benkar village; c) Phakding village on the lower terrace near a river bend; d) Jorsalle village on the lower terrace looking upstream; e) River section at Tok Tok village; f) Status of bank erosion downstream of Jorsalle in 1996; g) Situation of river section downstream of Nakchun in 1996; h) The unstable riverbank downstream of Ghat in 1996

Terrain Unit 4: Lower Terrace with wide valley

The characteristics of TU4 are:

- very wide river valleys, more or less straight reach, and settlements located at lower terraces (<5m),
- low chance of bank overtopping of lower terraces (<5m) by flood,
- lateral erosion of banks, mostly at bends within lower terraces (<5m), occasional progression of lateral erosion to upper terraces at weak geological formations, and
- sedimentation in river beds by dominant boulders larger than 50 cm and boulders less than 1m that are significant due to sedimentation at wide valleys.

TU4a – Dig Tsho (Upper reach of Langmoche Valley [Hilajun] and Thamo Teng)

The upper Langmoche river section, immediately after the outlet of the lake, is a wide river valley with river gradients of class S1 and S2. The upper reaches, closest to the breach, have suffered from severe lateral erosion. The Langmoche valley, which contains the villages of Langmoche and Chaserwa (tail end) had extreme riverbank erosion, extending for about 2 km downstream. The boulders (Figure 5.28a) deposited on the river valley are large where the area is closer to the lake outlet, becoming smaller further downstream. The widening of the river valley is conspicuous at Chaserwa village (Figure 5.28b), where the river eroded and outflanked its banks during the Dig Tsho GLOF.

Hilajun is located downstream of the Langmoche–Bhote Koshi confluence. The valley at Hilajun is wide and only the outer bend of the river was eroded, but the riverbed has extensive deposits of sediments. Boulders larger than 30 cm are dominant and are deposited as distinctive layers over large stretches of the river until Thamo Teng. The banks have many lateral erosion scars extending down to the lower river terraces, which have been overtopped at several locations (Figure 5.29).

Thamo Teng is located just upstream of the Thame gorge. The river valley at Thamo Teng experienced severe lateral erosion extending to the upper terraces. Catastrophic GLOFs have made this section of the Thame gorge more unstable. The lower to middle river terraces suffered the secondary impact of lateral erosion extending to upper terraces (Figure 5.30).

TU4b – Lake Imja Tsho (Upper Imja Valley, Pipre Goth [downstream of Chhukung] and Chhukung)

Chhukung village (Figures 5.3 and 5.31) is located on the end moraines of the Lhotse Nup and Nuptse glaciers. This area is separated from the median morain of the Lhotse and Imjatse glaciers by the Lhotse Khola (Figure 5.32) originating from the Lhotse glacier. The median moraine which separates the village from the Imja Khola is about 300m wide, 3 km long, and less than 40m high (Figures 5.3 and 5.32b). The hydrodynamic modelling showed inundation of Chhukung, but the field verification revealed less chance of such inundation. However, about 1 km downstream from the village, the valley narrows at the Pipre confluence. If this is blocked, the backwater can extend up to Chhukung.

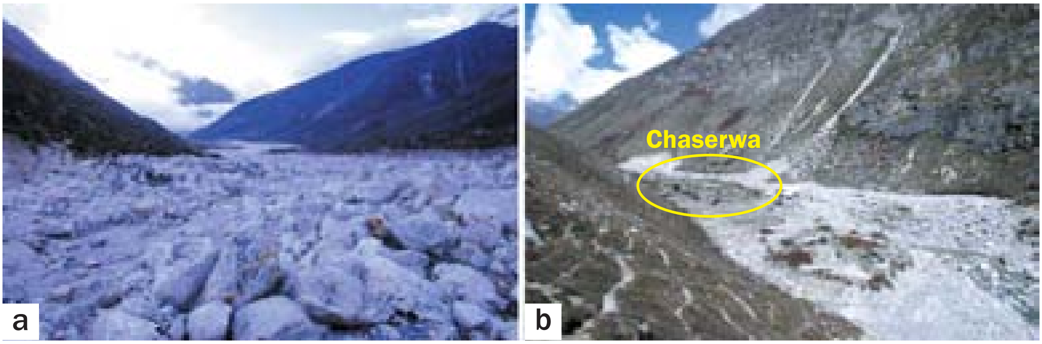


Figure 5.28: Terrace sediment characteristics of the Dig Tsho GLOF: a) Boulders deposited downstream; b) A wide river valley at the Chaserwa village lying on the lower terrace

Figure 5.29: Hilajun (foreground) and Thamo Teng (background). View downstream of Dig Tsho

Figure 5.30: Erosion and deposition along the Bhote Koshi River: a) Sediment deposition and erosion at a river bend; b) Extensive bank erosion and landslides observed upstream of Thame George; c) Thamo Teng village situated on middle terrace

Terrain Unit 5: Upper terrace with wide valley and river bends

The characteristics of TU5 are:

- moderately wide river valleys, with a more or less straight reach and settlements located on upper terraces (>10m),
- less chances of bank overtopping of upper terraces (>10m) by flood,
- lateral erosion of banks mostly at bends extending to lower terraces (<5m), occasional progressing of lateral erosion to upper terraces at weak geology, and
- sedimentation of river beds by dominant boulders of <0.3m and significant numbers of boulders of 0.5m at wide valleys.

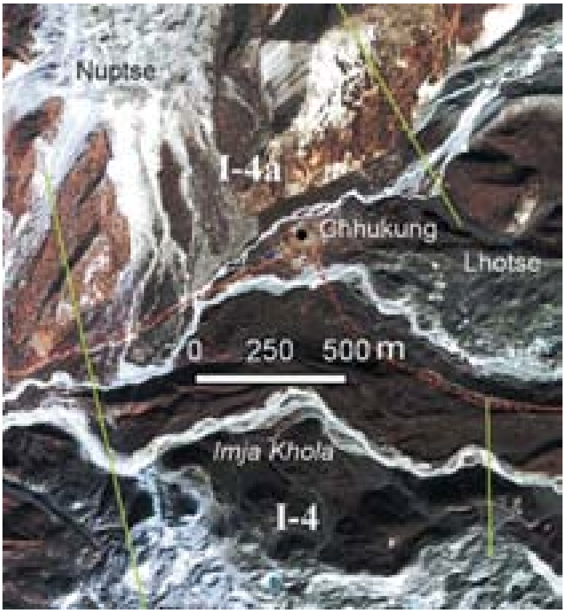


Figure 5.31: Chhukung village lying on the end moraines of the Lhotse Nup and Nuptse glaciers, near the confluence of the Imja and Lhotse Kholas

TU5a – Dig Tsho (Kamthuwa and Mingmo)

This terrain unit is characterised by upper terraces and wide river valleys; villages at Chamuwa, Kamthuwa, and Mingmo fit this profile. The villages of Kamthuwa and Mingmo are located in the upper Langmoche valley towards the breach. Since the valley is wide, settlements at this point are situated on upper terraces and a possible GLOF will have only minimal impact at Mingmo. Nevertheless, lateral erosion could extend towards the upper terraces (Figure 5.33). The dominant riverbed material consists of boulders larger than 1m at the breach becoming smaller than 50 cm, and a significant number of larger boulders (0.5–1m) at Mingmo. The Langmoche, Kamthuwa and Mingmo villages are sparsely populated. The area is mainly used for potato cultivation and as pasture in summer.

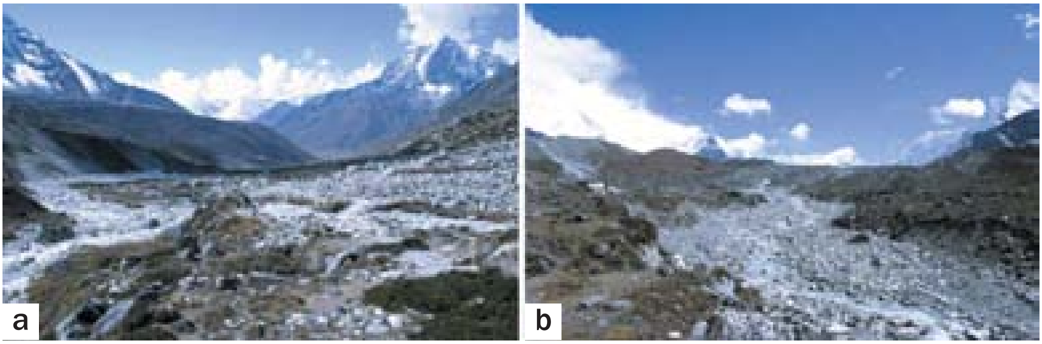


Figure 5.32: Situation in the vicinity of Chhukung: a) Downstream view (from Chhukung) of the confluence of the Imja Khola and the stream from Lhotse glacier. The median moraine is seen in the foreground; b) Upstream view of the Lhotse Khola, Chhukung is located on the left and the median moraine is on the right

Figure 5.33: Precarious positon of Mingmo located on the left bank of the Langmoche River with extensive bank erosion. View upstream

TU5b – Lake Imja Tsho (Dingboche, Pangmoche, Orsho, Syomare, Milingo, Debouche and Tengboche)

Dingboche village is the most densely populated area along the Imja valley and has a large number of hotels and lodges. The village is located at the river bend but the settlement is situated on upper terraces. In the river section, boulders of size <0.5m and cobbles are the dominant riverbed materials. A GLOF from Imja could cause severe lateral erosion at the river bends and sedimentation could occur (Figure 5.34a) in the downstream areas. The area containing the villages of Chhukung to Dingboche is similar to the section containing Hilajun and Thamu in the Dig Tsho GLOF area; however, the impact here will be much greater.

Dingboche village is located very high above the riverbed; the upstream and downstream sections of the village are wide and have a steep gradient. There is only a low possibility of a direct impact by a GLOF at Imja but lateral erosion at the outer bend of the river (nearest to the village) could endanger the houses closest to this riverbank.

Pangboche village is another densely populated area with many settlements, hotels, and lodges. The village is located on the upper terrace (Figure 5.34b). The outer bend of the village Tsuro (Figure 5.34c) confluence could suffer from severe bank erosion and subsequent sedimentation. This comparatively wide valley is similar to the confluence at Langmoche–Bhote Koshi and Bhote Koshi–Dudh Koshi. The settlements of Pangboche and Orsho (Figure 5.34d) would be affected only by secondary impacts of a GLOF event at Lake Imja Tsho, largely caused by propagation of bank erosion to higher elevations.

Both upstream and downstream of Pangboche village, the river section is compariatively wide and sedimentation will occur. The houses in the villages of Orsho, Syomare, Milingo,

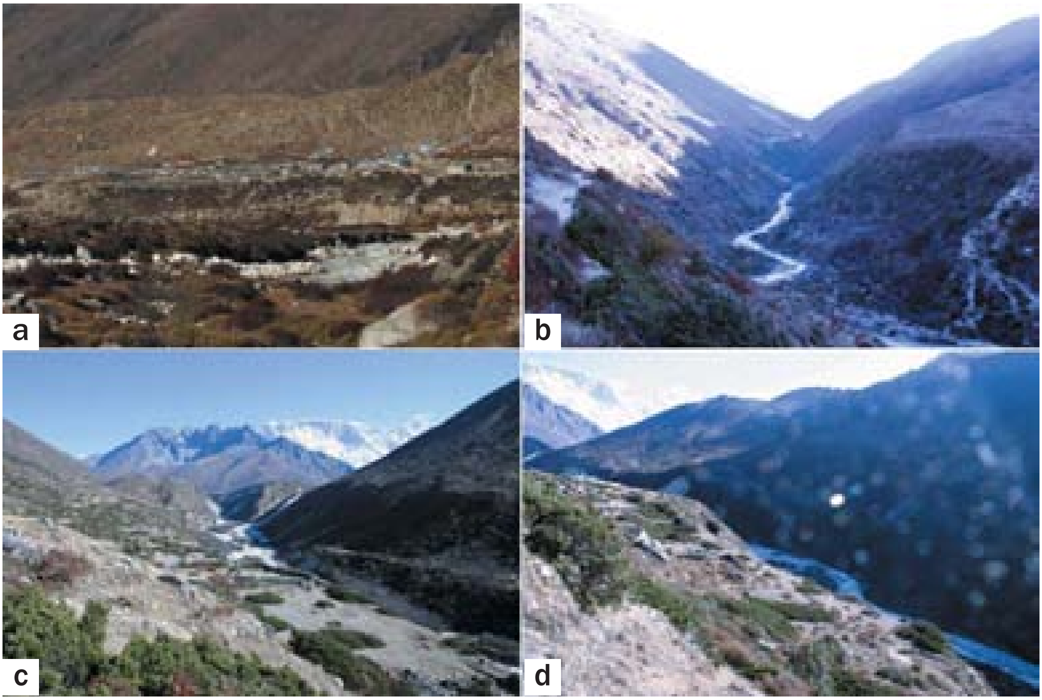


Figure 5.34: Villages and typical landforms in the Imja River valley: a) Dingboche village on the upper terrace of right bank; b) Upstream view depicting Pangmoche (left) and the micro-hydroelectric project (right); c) Tsuro (Churo) village on the right bank; d) Orsho village on the upper terrace of right bank

Debouche and Tengboche are situated at elevations much higher than the GLOF level; hence no direct impact of flood is expected in this area. However, Syomare village is located on a fossil landslide, even a small amount of lateral erosion at the toe would render the entire area unstable. At Milingo, landslides would extend to the upper terraces, away from the settlements, but on a trekking route.

Hazard assessment

In the Himalayan region, GLOFs are always a potential hazard, especially when there are glacial lakes at the headwaters of streams and rivers. GLOF hazard assessments can help in disaster preparedness, in the development of early warning systems, and in putting into place mitigation measures as needed. The following section is a hazard assessment of the Imja and Dudh Koshi valleys.

A GLOF from Lake Imja Tsho would pose an immediate danger to the downstream areas up to the village of Ghat. The level of hazard to a given downstream area can be assessed in advance based on the terrain unit and other field data collected along the Dudh Koshi sub-basin as discussed in the previous section. The level of hazard is classified according to the severity of damage an area might experience. Typically, five hazard areas are discussed, ranging in severity from 'very high hazard', a situation of total devastation or washout, to 'very low hazard', where the GLOF has only a minor impact.

Very high hazard

A 'very high hazard area' would be completely and immediately washed out in the case of a GLOF event. This type of area is mostly identified in Terrain Unit 1. At Imja, the very high hazard areas are immediately adjacent to the outlet and just downstream of the breach at the Imja constriction (which lies in the upper reaches of the Imja valley). These areas have no settlements, cultivation, or infrastructure. However, they do contain a famous trekking route to Island Peak.

High hazard

Areas are classified as 'high hazard' if they are at risk from both immediate primary impacts as well as secondary impacts of a GLOF event, such as lateral erosion and landslides. This type of area is mostly identified in Terrain Unit 2 where the strips are narrow, with sections of sharp bends. These areas either have no settlements (for example Larja Dovan) or settlements at high elevations away from the river (for example Lukla). In these areas, severe lateral erosion of bed and banks could have repercussions for areas considerably higher up and away from the water flow in the form of secondary events such as landslides. Any new infrastructure and settlements in this area should be considered as at risk from possible secondary impacts.

Syomare village is a typical example of a high hazard area. This village is situated on a fossil landslide but lies above the high flood level. Any slight lateral erosion at the toe will reactivate the landslide. This village also sits on a concave bend of the Imja Khola; in the case of a GLOF, the flow will reactivate the landslide by scouring its toe and will create a high risk to the village (Figure 5.35). The infrastructure that is at high risk consists of 3 small one-storey wooden house, 11 medium-sized chiselled cement-mortared houses, and 3 large chiselled cement mortared houses (Table 5.3).

Moderate hazard

An area is classified as 'moderate hazard' if there is a possibility of overtopping by the GLOF. Typically, these are low-elevation terraces. This type of area is identified in Terrain Unit 3. The villages of Ghat, Chutawa, Chermading, Phakding, and Benkar (Figure 5.36) can be categorised as such. These villages are populated and contain many domestic dwellings and commercial buildings as well as cultivated land and trekking routes. Both houses and cultivated land (at lower terraces <5m) were overtopped during the last Dig Tsho GLOF.

Figure 5.35: Concave bend of the Imja Khola at Syomare where bank scouring is expected in the case of a GLOF

Table 5.3: **Vulnerability of downstream valleys to potential Lake Imja Tsho GLOF**

Terrain Unit	Type Locality	Causes of Damage	Affected Infrastructure and Landuse	Infrastructure					Vulnerability (%)	Remarks
				Unit	Nr.	Storeys	Type	Class		
TU-II	Syomare	Landslide	House	no	3	1	S	4	100	Syomare on old landslide
		Landslide	House	no	11	1	M	1	100	
		Landslide	House (new)	no	3	1	L	1	100	New house
		Flood	House (NC)	no	2	2	M	2	100	10*50*2 and 10*30*2 (ft)
TU-III	Chermading	Flood	House (NC)	no	4	2			100	
		Flood	House (NC)	no	3	2			40	
		Flood	Cultivation	sq m					100	
	Phakding	Flood	House	no	3	2	M	2	50	right bank
		Flood	House	no	4	2	M		100	
		Flood	House	no	2	2	L		50	after bridge
		Flood	House	no	3	2	M		50	
		Flood	Cultivation	sq m					100	maize field
		Flood	House	no	3	2	M	2	25	
		Flood	Suspension Bridge	m	84				100	metal strip
	Benkar	Flood	Cultivation	sq m					100	vegetables and wheat
		Flood	House	no	4	1			100	wooden
		Flood	House	no	1	1			75	
		Flood	House	no	3	1			90	
		Flood	House	no	2	1			75	left bank of trails
		Flood	Suspension Bridge	m	120				25	
	Jorsalle	Flood	House	no	1	2	M	1	100	at narrow valley
		Flood	House	no	2	2	M	1	70	
		Flood	House	no	2	2	M	3	80	
TU-IV	Pangboche	Flood	MHE Project (15 KW)	no	1	1			100	old moraine,
		Flood	Cultivation						100	right bank
		Flood	Metal Bridge	m	10				100	
TU-V	Dingboche	landslide	House	no	4					

Types: S = small; M= medium; L = large
Class: 1 = chiseled stone block with cement plaster and zinc sheet; 2 = stone block with mud mortar; 3 = wooden house with stone wall; 4 = small goth type house.
NC = non-commercial other/off-trail house; C = Commercial house along a trail
Note: Forested areas extend up to Syomare village

The severity of the impact from a possible Lake Imja Tsho GLOF event is expected to be greater than that of the Dig Tsho GLOF. The settlement area at lower terraces in this zone is at moderate GLOF hazard, and secondary impact by landsliding of upper terraces is expected. The large number of sharp river bends at close intervals and the moderately wide river valley create a scenario where lateral erosion of lower terraces is inevitable. The houses in the settlements at Chermading, Phaking, Benkar, and Jorsalle villages and the trekking routes are highly vulnerable. In addition, the damage will in all likelihood lead to a chain reaction on the upper terraces in Ghat village. A detailed list of likely damage to houses (commercial and non-commercial) and agricultural lands is given in Table 5.3.

Figure 5.36: Phakding and Chermading villages lying on the lower terrace of the Dudh Koshi River

Low hazard

Areas in both lower and upper terraces in wide river valleys, as well as areas outward from normal debris flow, are considered 'low hazard areas' and are usually found in Terrain Units 4 and 5. Here the GLOF has little chance to do any direct damage but can still be destructive when it cuts across terraces and induces secondary landslides. Some houses at the extreme edge of the terraces could suffer damage. Villages like Tsuro, Dingboche, Orsho, and Pangboche belong to low GLOF hazard areas. Some houses in Dingboche village are located on the edge of upper terraces (Figure 5.37). Such houses could be affected by secondary phenomena from landslides propagated to upper terraces. The area upstream from Dingboche village is very wide; the section of the river between the Tsuro confluence and Dingboche could be an area where sediment accumulates.

Similarly, while the area upstream of Pangboche is wide, the downstream river valley is only moderately wide. Houses situated on upper terraces would not be directly impacted but cultivated areas (at lower elevations) could be affected. The generation plant and the tailrace of the micro hydropower station located on the lower terraces could be damaged by an Imja GLOF. This hydropower station generates 15 kW and supplies electricity to Pangboche and surrounding villages.

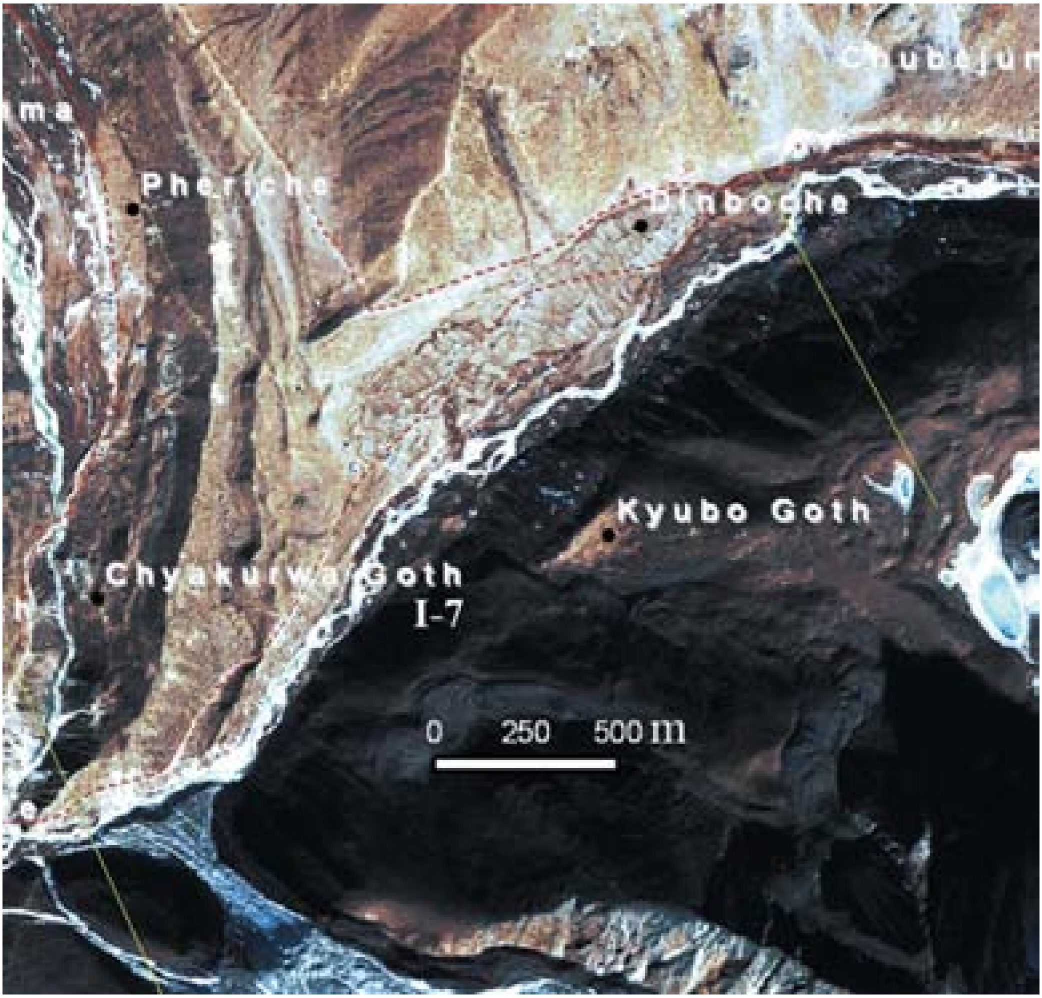


Figure 5.37: Dingboche village on the upper terrace in a wide valley of the Imja Khola

As a result of the past Dig Tsho GLOF, most of the suspension bridges are now constructed at higher elevations. An exception is the Hilajun metal bridge at the confluence of the Langmoche and the Bhote Koshi. The old bridge at Milingo was replaced by a new one at an elevation higher than the past GLOF effect. The wooden bridge at the Tsuro confluence, however, is in the flood hazard area and would be highly vulnerable to a GLOF event.

Very low hazard

Areas categorised as 'very low hazard' are low-lying terraces at some distance from the predicted direct path of the GLOF. Here the hazard would consist of backwater deviated due to obstruction in the debris flow – the chance of this type of event occurring is considered very low. This type of area is identified in Terrain Unit 4. Chhukung village lies on a fossil moraine one valley over from the Imja Khola valley. The flood routing predicted from the hydrodynamic model shows inundation of Chhukung village, but field verification suggests that the village would be inundated only under extraordinary conditions. Hence this area is classified as the lowest level hazard zone.

Vulnerability assessment

Vulnerability assessments were based on visual inspection and walkover surveys along the trekking routes, augmented by the modelling and flood routing results discussed in Chapter 4. The lateral or bed erosion and sedimentation from a possible Lake Imja Tsho GLOF to Larja Dovan is based on estimates made by comparing data from the Langmoche valley (which experienced a GLOF in the past). The Larja Dobhan lies below the confluence of the streams from the Lakes Dig Tsho and Imja Tsho. The area downstream from Larja Dovan has already experienced the Dig Tsho GLOF; an additional GLOF event in this valley would be catastrophic. The slope failure that was generated after the last GLOF event is still active in Ghat and in Phakding. A new GLOF event could trigger new instabilities in many places and reactivate the old ones.

The vulnerability of a given element at risk is based on the probability of a direct or indirect hit by the GLOF. The vulnerability of different infrastructure to a possible Imja GLOF is summarised in Table 5.3. Infrastructure was classified as either commercial or non-commercial and further classified as small, medium or large on the basis of a visual estimation of the coverage of the plinth area to less than 200 sq ft (20 sq m), 500 sq ft (50 sq.m), and more than 500 sq ft respectively. The buildings are further classified into four types: chiselled, cemented, mud-mortared, wooden houses, and small cattle-shed. Bridges are classified based on span, and agricultural land is measured simply in square metres.

Chapter 6

Early Warning Systems and Mitigation Measures

Early warning systems aim to detect impending GLOFs in sufficient time to relay a warning to people who might be affected so they can move to safer ground. Mitigation measures aim to reduce the risk by intervening to somehow change the physical structure. Different types of early warning systems and mitigation measures are in place in Nepal and Bhutan. Examples of early warning systems and mitigation measures from the Tsho Rolpa and Bhote Koshi valleys of Nepal, and Lunana region of Bhutan are described.

Early warning systems

Early warning systems in the Tsho Rolpa and Tama Koshi Valleys, Nepal

Tsho Rolpa is one of the most extensively studied glacial lakes and has received extensive media coverage. The Department of Hydrology and Meteorology Nepal (DHM) installed an early warning system in the villages of the Tama Koshi valley to warn people living in downstream areas. The GLOF early warning system, installed in April–May 1998, consists of two main components: a GLOF sensing system and a GLOF warning system.

GLOF sensing system

The sensing system detects the occurrence of a GLOF and transmits relevant information to the transmitter station to initiate the warning process. Six water level sensors are installed at the river channel (immediately downstream of the lake outlet) at Sangma Kharka to detect the onset of a breach. The sensors are connected by armoured and shielded cables to a transmitter station (Figure 6.1) located at a higher elevation within a distance of 80m from the sensors. In the event of a GLOF, the system detects and immediately relays the information. The information is received by all warning stations located downstream within two minutes of initiation of the flood. The warning system is fully automated, redundant and requires no human intervention.

Figure 6.1: The transmitter station of Sangma Kharka outside Lake Tsho Rolpa receives signals from sensors and transmits to other remote warning stations.

The remote station at Naa village has the dual function of forming part of the GLOF sensing system and providing local warning to the residents of Naa. The warning system is functioning, but there have been a few minor occurrences of false alarms due to shorts caused by moisture in the electrical system.

GLOF warning system

A series of 19 GLOF warning stations and relay stations are installed at the 17 villages in the Rolwaling and Tama Koshi valleys (Naa, Bedding, Jyablu, Gongar, Jagat, Totalabari, Bhorle, Singati, Pikhuti, Nagdaha, Nayapul, Sitali, Kirne, Khimtibesi, Haldibesi, Manthali and Rajagaon) (Figures 6.2, 6.3, and 6.4). In addition, a meteor-burst master station has been installed in the city of Dhanagadhi in western Nepal. The master station provides a communication link between remote stations located in the Rowaling and Tama Koshi valleys and the system monitoring station located in Kathmandu.

The GLOF warning systems are based on Extended Line of Site VHF radio technology (Bell et al. 2000). An early warning signal is triggered automatically when a GLOF is detected. Each village has an Meteor Communication Corporation (MCC) 545-transceiver unit mounted on a 4.67m self-supporting standard galvanized iron power pole. The master station has a phased array of four receiver antennas and one transmitter antenna. It receives signals from and sends signals to the remote stations via signal-reflected off-ionised meteor trails in the upper atmosphere. The operation of this component of the communication system is equipped with a computer. The station is connected to the local AC power supply with automatic switchover to and between two backup diesel generators.

An antenna is mounted on an extension to the pole and approximately 5m above the ground. Also mounted on the pole are a lightning rod and a solar panel. The MCC 545 unit, battery, and relay for the horn are mounted inside a sheet metal box with a lockable shelter attached to the pole (Figure 6.5). All cables are protected by a plastic conduit, covered by galvanised sheet metal and strapped to the pole. An air-powered horn is backed-up by an electric horn. The air horn is designed to operate off a charged air cylinder for a period of two minutes with a reserve for an additional one to two minutes in the event. The electric back-up horn will operate for four minutes. The air horn provides a sound of 80dB up to a minimum distance of 150m under the most adverse conditions (Bridges 99, 2001).

Figure 6.2: Early warning system installed at Gongar village. The systems consist of a solar panel, battery, antenna and amplifier with siren.

Figure 6.3: The early warning system installed at Bhorle village

The remote stations are powered by a 12V battery charged by a solar panel. The power for beyond the 'line-of-site' VHF signals as well as system configuration guarantees that any particular warning station can receive or transmit signals to the two immediately upstream and two immediately downstream stations. This ensures that a temporary failure at any particular station does not interrupt the transmission of warning signals to other villages. The system is automatically monitored hourly for battery voltages, forward and reverse transmit power, and sensor status from data monitoring stations at Khimti and in Kathmandu.

Figure 6.4: The early warning system installed at Jagat village

The master station has a phased array of four receiver antennas and one transmitter antenna. It receives signals from and sends signals to the remote stations via signal-reflected off-ionised meteor trails in the upper atmosphere. The operation of this component of the communication system is equipped with a computer. The station is connected to the local AC power supply with automatic switchover to and between two backup diesel generators.

Figure 6.5: An MCC 545 unit with 12 V batteries, air cylinder, and MCC-545A RF modem for relay, mounted inside a lockable shelter

A somewhat different and more intensive warning system is needed either during those short time periods when construction projects are taking place or for other reasons when greater risk is identified. For example, during the 1997 construction of the Tsho Rolpa GLOF Risk Reduction Project (TRGRRP), which aimed to lower the lake level by 3 metres, such early warning systems were installed in the Rolwaling and Tama Koshi valleys. These were housed at the army camps (lakeside) and at the police posts of the Naa and Bedding villages. Each army camp and police post was provided with a high frequency (HF) radio transceiver, and the army post at Naa had a backup set as well. 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 army post at the lakeside 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. (Radio Nepal was a natural choice since its signal is received in most at-risk places along the valley.) After completion of the first phase of the TRGRRP, the HF radio transceiver was removed from all the army camps and police posts.

Figure 6.6: GLOF Sensor and early warning system in the Bhote Koshi, (a) Sensor at River Level, (b) Sensor at Friendship Bridge, (c) Early warning system siren

Early warning system in the Upper Bhote Koshi valley, Nepal

The early warning system installed in the Upper Bhote Koshi Hydroelectric Project (UBKHEP) is similar to the one that is part of the TRGRRP. There are two remote sensing stations with data loggers near the Friendship Bridge designated to receive, analyse, and transmit data from sensors. When the water level increases significantly, the system transmits evacuation warning signals to the warning stations installed at the intake and the powerhouse (Figure 6.6). The fully redundant warning systems consist of seven GLOF detection sensors at the Friendship Bridge, one ultrasonic water level measuring device, and six float type water level switches (Figure 6.7). It operates on short-burst VHF radio signals using meteor burst technology. As a result, warning sirens are set off from compressed air horns, which transmit the sound of 127 dB at a minimum distance of 100 feet. There are five such stations along the river.

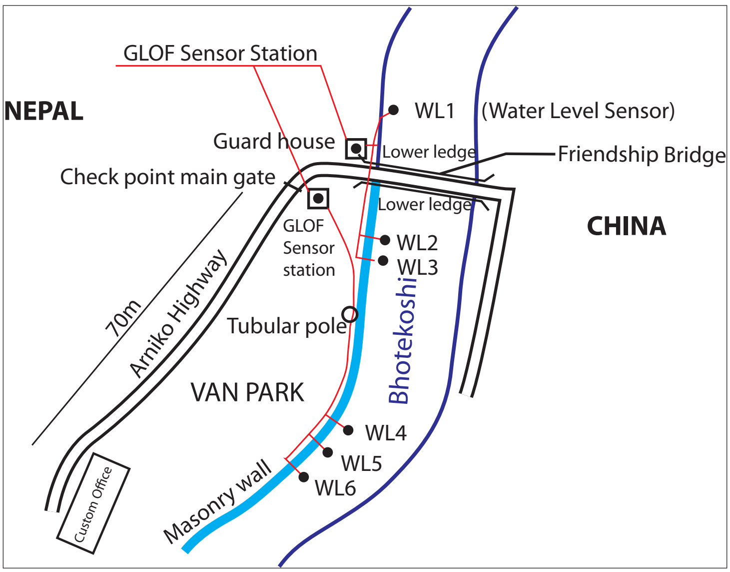


Figure 6.7: Location map of the GLOF sensor stations installed in the Bhote Koshi valley

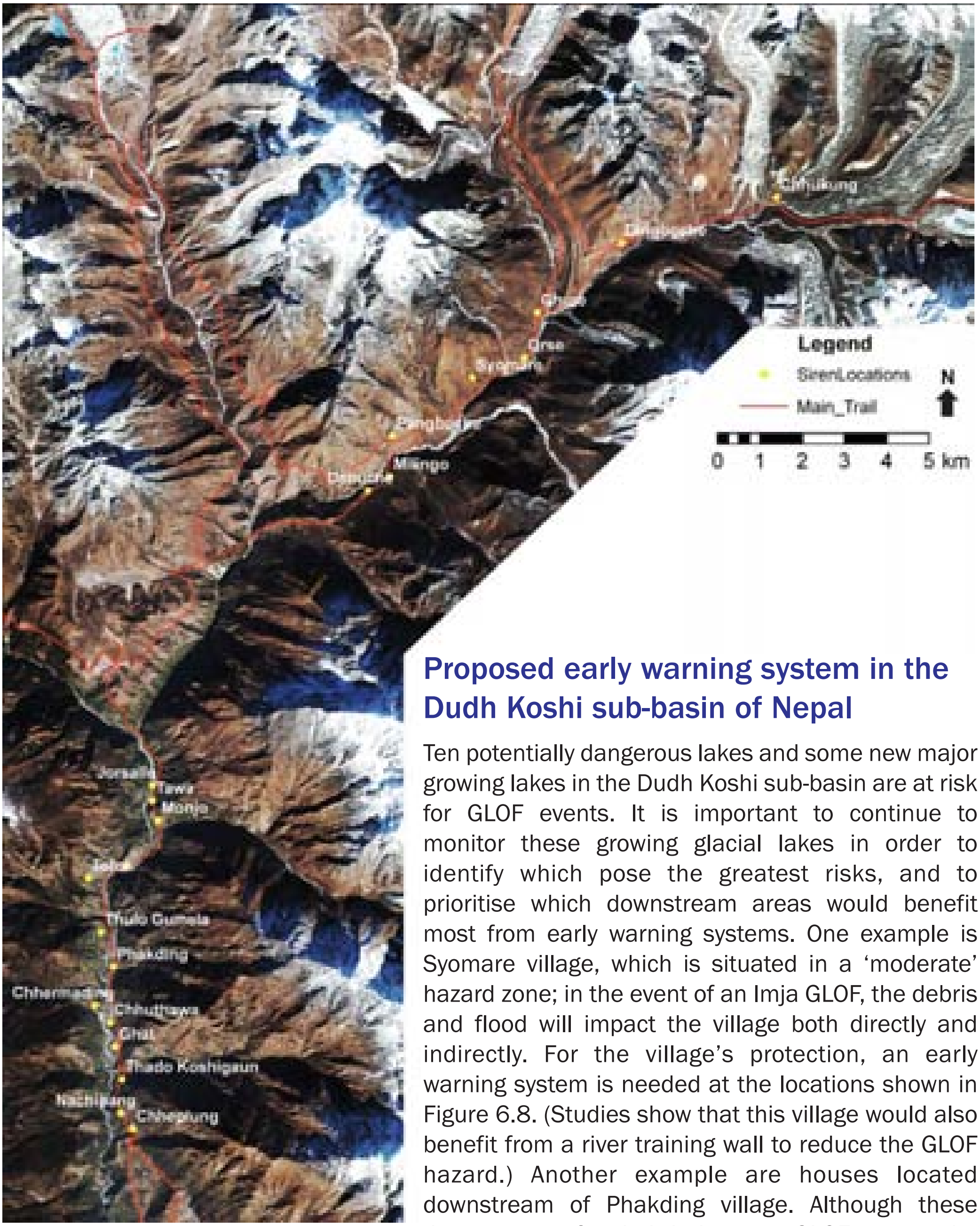


Figure 6.8: Proposed locations of early warning system in the Dudh Koshi valley

Proposed early warning system in the Dudh Koshi sub-basin of Nepal

Ten potentially dangerous lakes and some new major growing lakes in the Dudh Koshi sub-basin are at risk for GLOF events. It is important to continue to monitor these growing glacial lakes in order to identify which pose the greatest risks, and to prioritise which downstream areas would benefit most from early warning systems. One example is Syomare village, which is situated in a 'moderate' hazard zone; in the event of an Imja GLOF, the debris and flood will impact the village both directly and indirectly. For the village's protection, an early warning system is needed at the locations shown in Figure 6.8. (Studies show that this village would also benefit from a river training wall to reduce the GLOF hazard.) Another example are houses located downstream of Phakding village. Although these houses were flooded during past GLOF events, the number of houses and other buildings in the area continues to increase, despite local awareness that it is a flood-prone area, because Phakding is located on a major tourist trekking route. Houses located on lower terraces (mostly in Benkar, Phakding, and other low-lying areas) are prone to floods and secondary events such as lateral erosion, which extends to upper terraces. As an absolutely minimum measure, at least villages that were previously subjected to flooding and overtopping during the Dig Tsho GLOF, and which are known to be at risk, should be equipped with early warning systems.

Regular temporal monitoring using RADAR dataset in Nepal

Remote sensing has transformed the field of earth observation but it is not without its own inherent problems. Clouds can be a major hindrance to satellite imaging (particularly during the monsoon season) in the visible and infrared remote sensing range. Information missed due to cloud cover cannot be retrieved and is then accessible only by field observation. An alternative solution is microwave remote sensing. Since microwave sensing can penetrate cloud cover it is independent of weather conditions and is thus suitable for year-round monitoring of glacial lakes.

Radio detection and ranging (RADAR) is a system that operates in the ultra high-frequency (UHF) or microwave part of the radio frequency spectrum. Synthetic Aperture Radar (SAR) and Advanced Synthetic Aperture Radar (ASAR) aboard ENVISAT are two of the RADAR sensors operated by the European Space Agency (ESA). In a feasibility study, ICIMOD (with support from ESA) is looking at regular temporal RADAR monitoring of Lake Imja Thso. Since 2007, SAR and ASAR data are being used to monitor the growth of Imja Tsho and its vicinity. Although highly simplified, the growth pattern and activities at the glacier snout indicate a possible GLOF hazard. The rate of change can be particularly significant, and RADAR can be used to monitor as often as monthly.

Differences in the surface area of the lake are observed by examining colour composite images. A colour composite image is produced by superimposing images collected at different times where each time frame is assigned a colour. Figure 6.9 shows a composite image of Lake Imja Tsho produced by superimposing data from three different years.

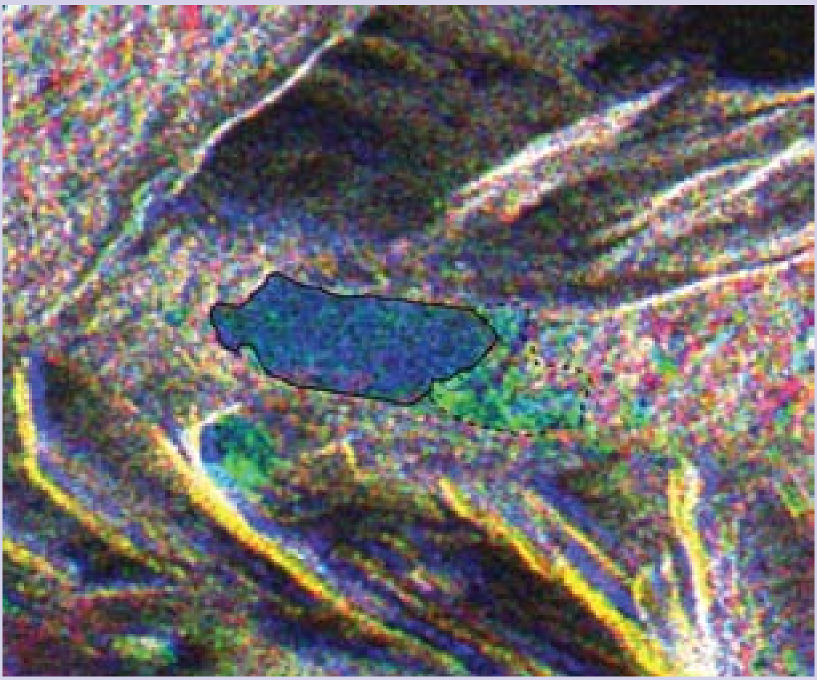


Figure 6.9: A colour composite image obtained by superimposing the RADAR images of Lake Imja Tsho taken in 1993 (red), 1996 (green), and 2005 (blue). The unbroken polygon represents the lake area in 1993 while the dashed polygon represents the increase in the lake area by 2005.

Early warning system in the Lunana region, Bhutan

A manually operated early warning system was installed in the Lunana region by the Flood Warning Section (FWS) under the Department of Energy (DoE). In this system, two staff members from the FWS are stationed in the Lunana lake area and are equipped with both a wireless set and a satellite telephone. They use these to report lake water levels on a regular basis and to issue warnings to downstream inhabitants (in the event of any indications of GLOF). A number of gauges have been installed along the main river as well as at the lakes. These are monitored at various stations at different time intervals 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 (Figure 6.10).

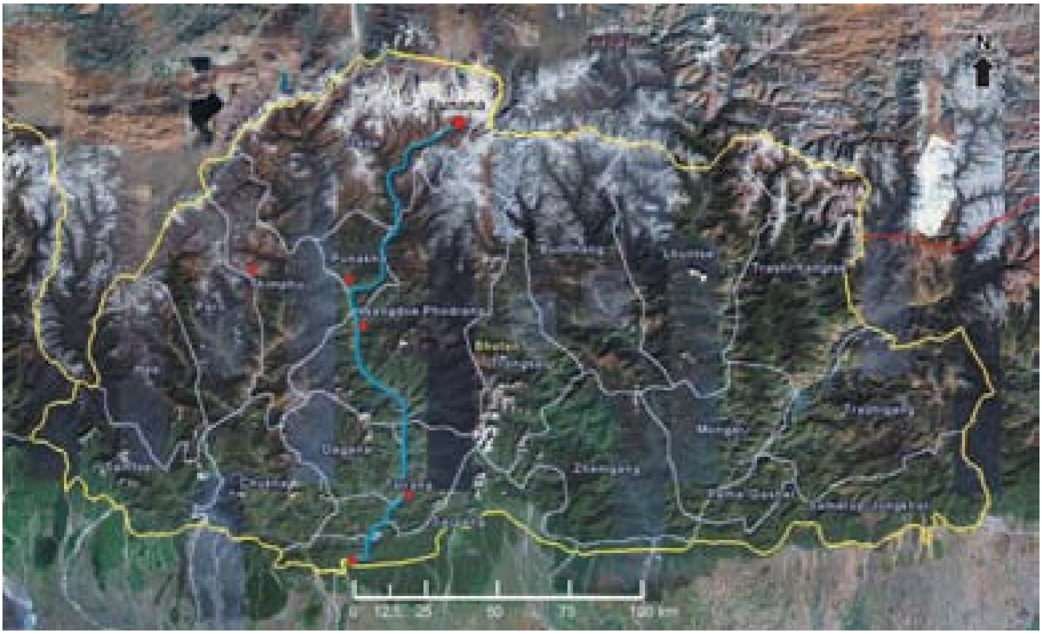


Image: Google Earth 2001

Figure 6.10: Manually operated early warning stations in the Pho Chu valley. Red dot: wireless station; Blue line: Pho Chu River

Mitigation Measures

Various methods and techniques are used to mitigate potential GLOF hazards in the Himalayas. If the environment permits, lowering the level of the lake water is usually considered the most effective mitigation measure. When the lake water level is reduced, the hydrostatic pressure exerted by the water on the moraine wall is correspondingly reduced, ultimately diminishing the risk of outburst from the lake. The lake water level can be reduced by the following methods:

- controlled breaching
- construction of an outlet control structure
- pumping or siphoning out the water from the lake
- boring a tunnel through the moraine barrier or under an ice dam

Examples of the first three of these can be found in Nepal and Bhutan with different rates of success, and are discussed below.

Mitigation measures in Tsho Rolpa Glacial Lake, Nepal

Tsho Rolpa is the only lake in Nepal where GLOF mitigation measures have been undertaken. Two main attempts both aimed to lower the water level in the lake. The first approach used siphon pipes to drain the water and left the moraine wall intact. The second approach used a channel cut through the end moraine to control the outflow of water.

Siphon pipes

In 1995 the Netherlands-Nepal Friendship Association successfully installed siphons, from the Wavin Overseas Company, the Netherlands (Figure 6.11), which were used to test the mechanisms and materials required to lower the level of Tsho Rolpa Lake. Three separate siphons, specially designed with fittings to increase the flow, were installed at the lake. The system of siphons consisted of about 100 HDPE plastic pipes and couplings, all of which were transported to the site by local people from the endangered villages. These plastic pipes were light enough that 5m sections could be carried by a single porter, flexible enough to accommodate the broken terrain, and rugged enough to withstand the extreme pressure, temperature, and unusually intense UV radiation. Assembly was possible without the need for skilled labour or special tools.

Figure 6.11: Siphon across the end moraine

The three inlet pipes were submerged 15m below the surface of the lake in the deeper part. Water was carried up over the moraine dam, 1.5m above the surface of the lake, and released at a stable site 200m below. The siphon pipes were 16 ft long and 0.25 inches thick with openings of 5.5 inches, and joint couples 0.8 inches thick. Tests of the trial installation showed that water was being evacuated at a rate of 170 l/sec, but this was not sufficient to have a noticeable impact on the level of the lake. Estimates indicated that an outflow of at least 30 times greater would be required to lower the lake level by 3m. The siphon system worked for 14 months without any maintenance. However, by May 1996, the system was dislocated at three points, and by September 1996 it was out of order. Two months later, for unexplained reasons, the siphon again began to function; however by August 1997 another joint had been broken. The system continued to function under less than optimal conditions (Bridges 99, 2001), and owing to lack of regular maintenance, the joint couplings broke very often. When the water was drained by an open channel outlet, the siphons were removed and distributed to the local people who used them for sewerage management (Figure 6.12).

Figure 6.12: The test siphons lying in an open store in Naa village

Open channel

In the second approach, the water level in the Tsho Rolpa glacial lake was lowered by opening a channel through the end moraine. The natural spillway of the lake is located in the centre of the end moraine. An outlet channel (70m long, 4.2m wide, 3m deep) was constructed on the left side of the end moraine (Figures 6.13 to 17).

Mitigation measures of Tsho Rolpa glacial lake to reduce its water level

Figure 6.13: View of the moraine-dammed lake with a natural spillway (left) and an artificial outlet (right)
Figure 6.14: Synoptic view of mitigation measures being implemented at the end moraine
Figure 6.15: Construction of the outlet canal and gates; the canal bed is being covered by geotextile.

Mitigation measures of Tsho Rolpa glacial lake to reduce its water level

Figure 6.16: Completed outlet canal to drain water

Figure 6.17: Spillway of the outlet canal on the moraine

The first phase of mitigation work was carried out by TRGRRP (Figure 6.18) of DHM in June 2000. The major part of the funding was provided by the Government of the Netherlands (US $2,988,625), and the Government of Nepal provided the remainder (US $115,414). The target of the project was to lower the level of the lake by 3m by the end of June of that year. Watermarks on the islands showed that the water level of the lake was lowered to that targeted depth (Figure 6.19).

Mitigation measures in Bhutan

Controlled breaching of the Raphstreng Tso, Bhutan

Controlled breaching can be accomplished in different ways, either by using explosives, by excavating, or even by dropping bombs from the air. A successful project of this type was conducted at Bogatyr Lake in Alatau, Kazakhastan, where explosives were used to excavate the outlet channel of the lake (Nurkadiloc et al. 1986). While this method is often effective,

Photo 6.18: Tsho Rolpa GLOF Risk Reduction Project (TRGRRP) of the Department of Hydrology and Meteorology

Figure 6.19: Watermarks on the islands located near the end moraine indicating the lowering of water level

there is always a risk of uncontrolled, regressive erosion of the moraine wall, which could lead to a too rapid lowering of the lake water level. Cases where there has been sudden dumping of huge volumes (6–10 million m^3) of water from a lake have been reported from Peru (Lliboutry et al. 1997a, b, c). In places like Lunana in the Bhutan Himalaya, where several glacial lakes exist adjacent to each other and where their moraine systems are interlinked, the use of explosives is not recommended since too much of the surrounding moraines that dam adjacent lakes in the vicinity may be destabilised.

After the 1994 Luggye Tso GLOF, several studies were conducted in the region to assess the GLOF risk from other lakes. The Raphstreng Tso, a moraine dammed glacial lake in the same area, was found to be in a critical state and immediate mitigation measures were proposed. Subsequently three phases of mitigation work were carried out on this lake from 1996 to 1998. The work was coordinated by the Ministry of Home and Cultural Affairs. The original aim was to reduce the water level by 20m but later this was revised to only about 4m (WAPCOS 1997). Since explosive means were considered too risky, manual excavation of the outlet to widen and deepen the opening was found to be the best option (Figure 6.20).

Controlled breaching, effected by purely manual methods without recourse to machinery or explosives, was considered the most suitable solution for the sensitive site at Raphstreng Tso. A channel, 78.5m long and 36m wide, was constructed at the outlet of this lake. The channel was manually widened and deepened using basic tools such as crowbars, pickaxes, and spades and eventually the lake water level was lowered by approximately 4m. The only drawback is that such manual methods are very labour-intensive and thus rather expensive. Similar mitigation work has already been proposed for the Thorthormi lakes (Brauner et al. 2003).

Figure 6.20: Raphstreng Tso outlet expanded by manually digging through the end moraine in 1998, see Figure 2.9 for location

Pumping or siphoning out water from the Raphstreng Tso, Bhutan

This method of lowering the lake water level was attempted on the Raphstreng Tso during the first mitigation phase in 1996. In total, 9 or 10 water pumps (power tiller heads) were used to pump the water out of the main lake for 24 hours. The team found that pumping has only a minimal effect and was rather expensive, especially since the pumps were operated on fuel that added considerably to overall transport and fuel costs. In fact, it had originally been decided that the pumps were to be used in conjunction with manual excavation work;

however, they were discarded after they were found to be not particularly effective at lowering the water level. Pumps were not used in the later two phases of the work (1997 and 1998) except to pump water out of specific (small) excavation sites.

Other groups have also reported the high costs involved in using pumps for siphoning. See for example Liboutry et al. (1977a, b, c) from Peru and USA. Considering the remoteness of the geographical locations in the Himalayas, pumping as a means of reducing the lake water level is not appropriate. It is difficult to operate the pumps in these places because hydro power is seldom available; the only alternative is fuel, which is expensive and needs to be transported. The earlier inventory reported successfully using smaller and more manageable size pumps on smaller lakes, where they can be quite effective.

Hazard mapping in Bhutan a tool for decision-making

As discussed in the previous chapter for the Imja and Dudh Koshi valleys, hazard mapping can be applied in downstream areas where there are settlements and infrastructures and where people are planning for further development activities. Following the old adage that prevention is better than cure, hazard zonation mapping is relatively inexpensive and can help prevent disasters by making people aware so that they build beyond the reach of GLOF hazard areas. Results on hazard and risk mapping can be shared among relevant stakeholders and planners of development activities to ensure that infrastructure such as roads, buildings, hydropower, and bridges are built well away from high-risk areas.

Being a mountainous country, most of the population of Bhutan is settled along the fertile valley bottoms of major river basins, many of which are vulnerable to GLOFs. During the last phase of the Austrian-Bhutan project, a hazard zonation mapping was carried out along the Pho Chu River from Lunana (lake area) to Khuruthang in Punakha Dzongkhag. The main output from their work was a hazard map delineating areas along the Pho Chu River into different hazard zones. Similar mapping programmes are being proposed for Chamkhar Chu in Bumthang Dzongkhag and the remaining parts of Puna Tsang Chu, downstream from Khuruthang to Kalikhola at the border area.

Conclusion

Chapter 7

Conclusions

The earth's average surface temperature has been increasing since the end of the Little Ice Age. Over the last one hundred years, the temperature has increased by 0.3 to 0.6ºC. There are predictions that by 2100 the temperature of the Indian sub-continent may increase further by 3.5 to 5.5ºC due to global warming. While the contribution of human activity to global climate change is hotly debated, the retreat of glaciers in the Himalaya is compelling evidence that a change is indeed taking place. Glacial environments are especially sensitive to the impacts of climate change since temperature changes are more pronounced at higher altitudes, and this and other studies show that Himalayan glaciers have been melting at unprecedented rates in recent decades. One phenomenon associated with glacial retreat is the formation of glacial lakes at the terminal moraine. As the size of these lakes increases, so too does the risk of breaching of the unstable moraine dam, with a sudden release of the stored water giving rise to a 'glacial lake outburst flood' or GLOF. Most of the glacial lakes in the Himalaya have appeared within the last five decades, and the region has faced devastating consequences as a result of such floods.

The present study aimed to investigate the impact of climate change on glaciers and glacial lakes in the Himalayas based on empirical evidence and time-series data and information. The Dudh Koshi sub-basin of Nepal and the Pho Chu sub-basin of Bhutan are two known hotspots of glacial activity and have both witnessed devastating GLOFs in the past, thus these two areas were chosen as the focus of the case studies. The studies revealed some interesting insights on retreating glaciers and the growth of glacial lakes. The main findings were as follow.

- It is apparent that the glacier retreat rate has accelerated in recent times as compared to the 1970s. The valley glaciers and small glaciers are retreating fast. The Imja glacier retreated at an average rate of 42m per year in the period from 1962 to 2000. The retreat rate increased to 74m per year during 2001 and 2006, when it became one of the fastest-retreating glaciers in the Himalayas.
- Some of the smaller glaciers in Bhutan have completely disappeared; they could not be found on the satellite images of 2000–2001. In the Bhutan Himalaya the average retreat rate of glaciers was around 30m per year between 1963 and 1993. Some of the glaciers in the Lunana region of the Pho Chu sub-basin were retreating as fast as 57m per year in 2001, with an increase in retreat rate as high as 800% since 1970.
- During a glacier retreat, there is a high probability of formation of new lakes, as well as merging and expansion of existing ones, at the toe of a valley glacier. In the Dudh Koshi sub-basin of Nepal, the total number of lakes has decreased by 37%, but their total area has increased by 21%. Similarly in the Pho Chu sub-basin of Bhutan, the total number of lakes has decreased by 19% but the total area has increased by 8%.
- The Luggye Tso in the Pho Chu sub-basin of Bhutan, from which a GLOF originated in 1994, is once again in the process of enlargement. The Thorthormi glacier in Bhutan had no supraglacial ponds during the 1950s, but now there is a cluster of newly formed

supraglacial lakes which are merging. If this trend continues, they will further merge to form a large lake posing a serious GLOF threat in the near future.

The study also looked at methodologies for carrying out vulnerability and hazard assessment, and discussed possible early warning systems and suitable mitigation measures to reduce the adverse impacts of a GLOF. The main findings of these investigations were as follows.

- Hydrodynamic modelling of a potential GLOF can provide useful information for indicative impacts on life and property downstream. The results of such a model for the Imja and Raphstreng glacial lakes provides important information such as flood height, flood routing and arrival time, and potential discharge from a GLOF, which are all necessary parameters when devising an early warning system.
- The terrain classification of a past GLOF-affected valley can provide valuable information on the anticipated extent of damage in a particular terrain type. It is also useful for assessing the vulnerability of similar terrain in other valleys with potential GLOFs. The hazard assessment of the Imja Tsho indicated that the lower terraces at the Ghat, Chutawa, Chermading, Phakding, Benkar, Tawa, and Jorsalle villages have a possibility of overtopping by a GLOF.
- GLOF mitigation measures and commissioning of early warning systems are daunting and challenging tasks, and also quite expensive. Satellite-based techniques using RADAR imageries may prove a useful approach for monitoring a glacial lake independent of local weather conditions. Monitoring of Lake Imja Tsho using ESA RADAR satellite imagery provided a useful means for detecting growth (change) of the lake over a short time (as quickly as monthly). Such a technique may prove useful for issuing early warnings in a cost effective manner.

Climate change will continue to be a pressing global concern for the foreseeable future. Melting of glaciers warrants a concerted attempt to improve our scientific understanding of the impact of climate change. It is only by investigating much larger areas, that it will really be possible to assess the effects that the change in global climatic patterns is having in the Himalayas. The methodologies presented in this publication provide a basis for further investigations of other hotspots in the region, and can be a model for assessing the impact of climate change on glaciers, glacial lakes, and associated hazards as well as room for refining. Action is needed by the international community to safeguard the precious natural resources of this relatively unexplored, but spectacular, region of the world .

References

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, International Association of Hydrological Sciences (IAHS) Publ. No. 264, pp 165-175. Wallingford: IAHS Press

Ageta, Y.; Naito, N.; Nakawo, M.; Fujita, K.; Shakar, K.; Pokhrel, A.P.; Wangda, D. (2001) 'Study Project on the Recent Rapid Shrinkage of Summer Accumulation Type Glaciers in the Himalayas, 1997-1999'. In *Bull. Glacial. Research*, 18: 45-49

Asahi, K.; Kadota, T.; Naito, N.; Ageta, Y. (2006) 'Variations of Small Glaciers since the 1970s to 2004 in Khumbu and Shorang Regions, Eastern Nepal'. In *Data Report 4* (2001-2004), *Glaciological Expedition in Nepal (GEN) and Cryosphere Research in the Himalaya (CREH)*, pp 109-136. Kathmandu: HMG of Nepal, Department of Hydrology and Meteorology and Graduate School of Environmental Studies, Nagoya University

Bajracharya, S.R.; Mool, P.K. (2004) 'Potential Glacial Lake Outburst Floods from Major Glacial Lakes in Nepal in the Event of a Large Earthquake'. In Proceedings of the seminar and workshop on the Potential for Landslides in Nepal in the Event of a Large Earthquake, held 4-6 August 2004, Kathmandu Nepal, organised by the Mountain Risk Engineering Unit, Tribhuvan University, and University of Durham United Kingdom, pp 1-10. Kathmandu: Mountain Risk Engineering Unit, Tribhuvan University

Bajracharya, S.R.; Mool, P.K. (2005) 'Growth of Hazardous Glacial Lakes in Nepal'. In *Proceedings of the JICA Regional Seminar on Natural Disaster Mitigation and Issues on Technology Transfer in South and Southeast Asia,* Sep 30 to 13 October 2004, pp 131-148. Kathmandu: Department of Geology, Tri-Chandra Campus, Tribhuvan University

Bajracharya, S.R.; Mool, P.K. (2006b) *Impact of Global Climate Change from 1970s to 2000s on the Glaciers and Glacial Lakes in Tamor Basin, Eastern Nepal*. Unpublished report for ICIMOD, Kathmandu

Bajracharya, S.R.; Mool, P.K.; Shrestha, B.R. (2006a) 'The Impact of Global Warming on the Glaciers of the Himalaya'. In Proceedings of the International Symposium on Geo-disasters, Infrastructure Management and Protection of World Heritage Sites, 25-26 Nov 2006, pp 231-242. Kathmandu: Nepal Engineering College, National Society for Earthquake Technology Nepal, and Ehime University Japan

Baker, M.; Ekwurzel, B. (2006) *Global Warming Facts*. Washington DC: Union of Concerned Scientists

Bell, W.W.; Donich T.; Groves, K.L.; Sytsma, D. (2000) 'Tsho Rolpa GLOF Warning System Project'. In *Proceedings 28th IAHR Congress, Graz*. Available at www.iahr.org/membersonly/grazproceedings99/doc000/000/175. htm

Bhargava, O. N. (1985) *Geology, Environmental Hazards and Remedial Measures of the Lunana Area, Gasa Dzongkhag: Report of 1995 Indo-Bhutan Expedition*. Delhi: Geological Survey of India

Brauner, M.; Leber, D.; Hausler, H. (2003) *Glacier Lake Outburst Flood (GLOF) Mitigation Project, Lunana, Bhutan, Technical Mitigation Measures Thorthormi Outlet.* Vienna: Geocenter, Department of Geological Sciences, University of Vienna

Bridges 99 (2001) *Chronology of Tsho Rolpa GLOF Hazard Response, the Dutch Connection,* Internet discussion 'Bridge 99'. Available at www.mountainlegacy.net/gloftsho-rolpa-04.html

Cenderelli, D.A.; Wohl, E.E. (2001) 'Peak Discharge Estimates of Glacial-lake Outburst Floods and "Normal" Climatic Floods in the Mount Everest Region, Nepal'. In *Elsevier Geomorphology,* 40: 57-90

CSE (2002) 'Melting into Oblivion'. In *Down To Earth*, 15 May 2002

Department of Energy (2004) *The 2003-2022 Power System Master Plan*, Chapter 10. Unpublished report by the Department of Energy, Thimphu, Bhutan

DHM (1996) *Glacier Lake Outburst Flood Study of the Tama Koshi Basin*. Draft Report prepared by BPC Hydroconsult, November 1996 for the Department of Hydrology and Meteorology, Kathmandu, Nepal

Dobhal, D.P.; Gergan, J.T.; Thayyen, R.J. (1999) 'Recession of Dokriani Glacier, Garhwal Himalaya – An overview'. In *Proceedings of Symposium on Snow, Ice and Glaciers, A Himalayan Perspective*, Abstracts, pp 30-33. Delhi: Geological Survey of India

Dorji, Y. (1996) *Glaciers and Glacial Lakes Feeding Pho Chu and the Risk Associated with These Lakes*. Thimphu: Geological Survey of Bhutan

Dyhrenfurth, G. O. (1955) *To The Third Pole - The History of the High Himalaya,* 1st UK Edition. London: Ex Libris, Werner Laurie

Faust, E. (2005) *Climate Review 2005*, Topics Geo, Annual Review: Natural Catastrophes 2, Knowledge Series. Munich (Germany): Munchener Ruckversicherungs-Gesellschaft

Fujita, K.; Kadota, T.; Rana, B.; Shrestha, R.B.; Ageta, Y. (2001) 'Shrinkage of Glacier AX010 in Shorong Region, Nepal Himalayas in the 1990s'. In *Bulletin of Glaciological Research,* 18: 51-54

Fushimi, H.; Ikegami, K.; Higuchi, K.; Shankar, K. (1985) 'Nepal Case Study; Catastrophic Floods'. In *IAHS (*International Association of Hydrological Sciences) *Publication 149*, pp 125-130. Wallingford: IAHS Press

Galey, V.J. (1985) *Glacier Lake Outburst Flood on the Bhote/Dudh Kosi, August 4, 1985*, WECS Internal Report. Kathmandu: WECS

Gansser, A. (1970) 'Lunana – the Peaks, Glaciers and Lakes of Northern Bhutan'. In *The Mountain World*, 1968/69:117-131

GEN; CREH; NU; DHM (2006) *Data Report 4 (2001-2004),* GEN 2001-2002: *Imja Glacier Lake in Khumbu, East Nepal*. Kathmandu: DHAS and DHM

Geological Survey of Bhutan (1999) *Glaciers and Glacier Lakes in Bhutan*. Thimphu: Ministry of Trade and Industry

Hasnain, S.I.; Ahmad, S.; Kumar, R. (2004) 'Impact of Climate Change on Chhota Shigri Glacier, Chenab Basin, Gangotri Glacier, Ganga Headwater in the Himalaya'. In *Proceedings of Workshop on Vulnerability Assessment and Adoption Due to Climate Change on Indian Water Resources, Coastal Zones and Human Health, 27-28 June 2003, New-Delhi, India*, pp 1-7. Delhi: Govt. of India, Ministry of Environment and Forests

IPCC (2001a) *Climate Change 2001: The Scientific Basis,* Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press

IPCC (2001b) *Climate Change 2001: Impacts, Adaptation and Vulnerability,* Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Cambridge University Press

IPCC (2007) *IPCC Fourth Assessment Report – Climate Change 2007*: *Working Group 1, The Physical Science Basis, Summary for Policymakers*. (in press, available at http://ipcc-wg1.ucar.edu/wg1/wg1-report.html)

Ives, J.D. (1986) *Glacial Lake Outburst Floods and Risk Engineering in the Himalaya*, Occasional Paper No. 5. Kathmandu: ICIMOD

Kadota, T.; Fujita, K.; Seko. K.; Kayastha, R.B.; Ageta, Y. (1997) 'Monitoring and Prediction of Shrinkage of a Small Glacier in the Nepal Himalayas'. In *Annals of Glaciology,* 24: 90-94

Kadota, T.; Seko, K.; Aoki,T.; Iwata,S.; Yamaguchi, S. (2000) 'Shrinkage of Khumbu Glacier, East Nepal from 1978 to 1995'. In *Debris-Covered Glaciers*, Proceedings of a workshop held in Seattle, Washington, USA, September 2000, IAHS (International Association of Hydrological Sciences) Publication No. 264, pp 235-243. Wallingford: IAHS Press

Karma (2005) *Bhutan Himalayas: The Little Third Polar Region,* Bhutan Geology, Newsletter, No.8. Thimphu: Royal Government of Bhutan, Ministry of Trade and Industry, Department of Geology and Mines

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'. In *Bull. Glaciological Research* (Japanese Society of Snow and Ice), 20: 29-40

Kulkarni, A.V.; Rathore, B.P.; Suja, A. (2004) 'Monitoring of Glacial Mass Balance in the Baspa Basin using Accumulation Area Ratio Method'. In *Current Science*, 86 (1): 101-106

Lal, M. (2002) *Possible Impacts of Global Climate Change on Water Availability in India,* Report to Global Environment and Energy in the 21st Century. New Delhi: Indian Institute of Technology

Leber, D.; Hausler, H.; Brauner, M.; Wangda, D. (2002) *Glacier Lake Outburst Flood Mitigation Project Phase III (2000-2002), Lunana (Bhutan).* Vienna: University of Vienna, and Thimphu: Department Geology and Mines

Lliboutry, L.; Arnoa, B.M.; Schnieder, B. (1977a) 'Glaciological Problems set by the Control of Dangerous Lake in Cordillera Blanca, Peru; Part I Historical Failures of Morainic Dams, their Causes and Prevention'. In *Journal of Glaciology*, 18 (79): 239–254

Lliboutry, L.; Arnoa, B.M.; Schnieder, B. (1977b) 'Glaciological Problems set by the Control of Dangerous Lake in Cordillera Blanca, Peru; Part II Movement of a Covered Glacier Embedded within a Rock Glacier'. In *Journal of Glaciology*, 18(79): 255–274

Lliboutry, L.; Arnoa, B.M.; Schnieder, B. (1977c) 'Glaciological Problems set by the Control of Dangerous Lake in Cordillera Blanca, Peru; Part III Studies of Moraines and Mass Balances at Safund'. In *Journal of Glaciology*, 18(79): 275–290

Matny, L. (2000) 'Melting of Earth's Ice Cover Reaches New High'. In *Worldwatch News Brief*, 06 March 2000

Mayweski, P.; Jaschke, P.A. (1979) '*Himalaya and Trans Himalayan Glacier Fluctuation Since A. D. 1812'*. In *Arctic and Alpine Research,* 11(3): 267-287

Meteor Communications Corporation - Products – MCC - 520B/C, available at www.meteorcomm.com/products/prod_mcc_520bc.aspx?pr=1

Milankovitch, M. (1920) *Théorie Mathématique des Phénomenes Thermiques Produits par la Radiation Solaire*. Paris: Gauthier-Villars

Mool, P.K.; Bajracharya, S.R.; Joshi, S.P. (2001a) *Inventory of Glaciers, Glacial Lakes, and Glacial Lake Outburst Flood Monitoring and Early Warning Systems in the Hindu Kush-Himalayan Region – Nepal*. Kathmandu: ICIMOD

Mool, P.K.; Bajracharya, S.R.; Joshi, S.P. (2001b) *Inventory of Glaciers, Glacial Lakes, and Glacial Lake Outburst Flood Monitoring and Early Warning Systems in the Hindu Kush-Himalayan Region – Bhutan*. Kathmandu: ICIMOD

Mool, P.K.; Tao, C.; Bajracharya, S.R. (2004) *Monitoring of Glaciers and Glacial Lakes from the 1970s to 2000 in Poiqu basin, Tibet Autonomous Region PR China*. Kathmandu: ICIMOD (unpublished)

Mool, P.K.; Bajracharya, S.R.; Shrestha, B.R. (2005a) 'Inventory of Glaciers and Glacial Lakes and the Identification of Potential Glacial Lake Outburst Floods (GLOFs) Affected by Global Warming in the Mountains of India, Pakistan and China/Tibet Autonomous Region (APN 2004-03-CMY–Campbell)'. In *APN Newsletter*, 11(4): 6-7

Mool, P.K.; Bajracharya, S.R.; Shrestha, B.R. (2005b) 'Glaciers, Glacial Lakes and Glacial Lake Outburst Floods in the Hindu Kush-Himalaya'. In *Proceedings of the International Karakorum Conference, 25-27 April 2005*, Islamabad, Pakistan, Abstract Volume, pp 80-82. Pakistan Academy of Geological Sciences & Ev-K^2-CNR Committee of Italy

Naito, N.; Nishikawa, D.; Ageta, Y. (2000) 'Research Report on Glaciers, Glacier Lakes and Climate in Bhutan Himalayas, 1999'. In *Seppyo (Japanese Journal of Snow and Ice)*

Nurkadilov, L.K.; Khegai, A.U.; Popov, N.V. (1986) 'Artificial Draining of an Outburst-dangerous Lake at the Foot of Surging Glacier'. In *Data of Glaciological Studies*, 18: 220-221

Philip, G.; Sah, M.P. (2004) 'Mapping Repeated Surges and Retread of Glaciers Using IRS-1C/1D Data: A Case Study of Shaune Garang Glacier, Northwestern Himalaya'. In *International Journal of Applied Earth Observation and Geoinformation,* 6(2): 127-141

Richardson, S.D.; Reynolds, J.M. (2000) 'An Overview of Glacial Hazards in the Himalayas.' In *Quaternary International,* 65/66(1): 31-47

Sharma, A.R.; Ghosh, D.K.; Norbu, P. (1986) *Lunana Lake Expedition -1986*, Field report of Geological Survey of India, Bhutan Unit. Samtse: Geological Survey of India and Geological Survey of Bhutan

Shrestha, A.B.; Wake, C.P.; Mayewski, P.A. Dibb, J.E. (1999) 'Maximum Temperature Trends in the Himalaya and its Vicinity: An Analysis Based on Temperature Records from Nepal for the Period 1971-94'. In *Journal of Climate*, 12: 2775-2767

Shukla, S.P.; Siddiqui, M.A. (1999) 'Recession of the Snout Front of Milam Glacier, Goriganga valley, District Pithoragadh, Uttar Pradesh'. In *Proceedings of Symposium on Snow, Ice and Glaciers – A Himalayan Perspective,* Abstract Vol. pp 27-29. Delhi: Geological Survey of India

Srivastava, D. (2003) 'Recession of Gangotri Glacier'. In *Proceedings of Workshop on Gangotri Glacier*, Lukhnow, Abstracts, pp. 4-6. Delhi: Geological Survey of India

Surendra, K.; Dobhal, D.P. (1994) 'Snout Fluctuation Study of Chhota Shigri Glacier Lahaul and Spiti District, Himachal Pradesh. In *Journal Geological Society of India*, 44: 581-585

Thakur, V.C.; Virdi, N.S.; Gergan, J.T.; Mazari, R.K.; Chaujar, R.K.; Bartarya, S.K.; Philip, G. (1991) *Report on Gaumukh. The Snout of the Gangotri Glacier.* Unpublished report submitted to Department of Science and Technology, New Delhi

Thomas, R.K.; Kevin, E.T. (2005) 'What is Climate Change?' In Lovejoy, T. E.; Hannah, L. (eds) *Climate Change and Biodiversity,* p.15-28. New Delhi: TERI

USACE (2004) HEC-RAS 3.1.2 *Users Manual*, US Army Corps of Engineers

Vohra, C.P. (1981) 'Note on Recent Glaciological Expedition in Himachal Pradesh'. In *Geol. Survey of India Spec. Publ. 6*, pp 26-29. Delhi: Geological Survey of India

Vuichard, D.; Zimmerman, M. (1987) 'The 1985 Catastrophic Drainage of a Moraine-dammed Lake, Khumbu Himal, Nepal: Cause and Consequence'. In *Mountain Research and Development*, 7(2): 91-110

WAPCOS (1997) Raphstreng Lake, Lunana (Bhutan): *Report on Flood Mitigatory Measures (Phase 1 -1996)*. -IV + 52. New Delhi: WAPCOS

Watanabe, T.; Rothacher, D. (1996) 'The 1994 Lugge Tso Glacial Lake Outburst fLood, Bhutan Himalaya'. In *Mountain Research and Development*, 16: 77-81

Watanabe, T.; Ives, J.D.; Hammond, J.E. (1994) 'Rapid Growth of a Glacial Lake in Khumbu Himal, Himalaya: Prospects for a Catastrophic Flood'. In *Mountain Research and Development*, 14(4): 329-340

Watanabe, T.; Kameyama, S.; Sato, T. (1995) 'Imja Glacier Dead-Ice Melt Rates and Changes in a Supra-glacial Lake, 1989-1994, Khumbu Himal, Nepal: Danger of Lake Drainage'. In *Mountain Research and Development*, 15(4): 293-300

WECS (1987) *Study of Glacier Lake Outburst Floods in the Nepal Himalayas, Phase I, Interim Report*, May 1997, WECS Report No. 4/1/200587/1/1, Seq. No. 251. Kathmandu: WECS

WECS (1993) *Glacier Lakes and Their Outburst Floods in the Nepal Himalaya*. Kathmandu: WECS

WHO/WMO/UNEP (2003) *Climate Change and Human Health: Risks and Responses, Summary*. Geneva: WHO/WMO/UNEP

WWF Nepal Program (2005) *An Overview of Glaciers, Glacier Retreat, and Subsequent Impacts in Nepal, India and China*. Kathmandu: WWF Nepal Program

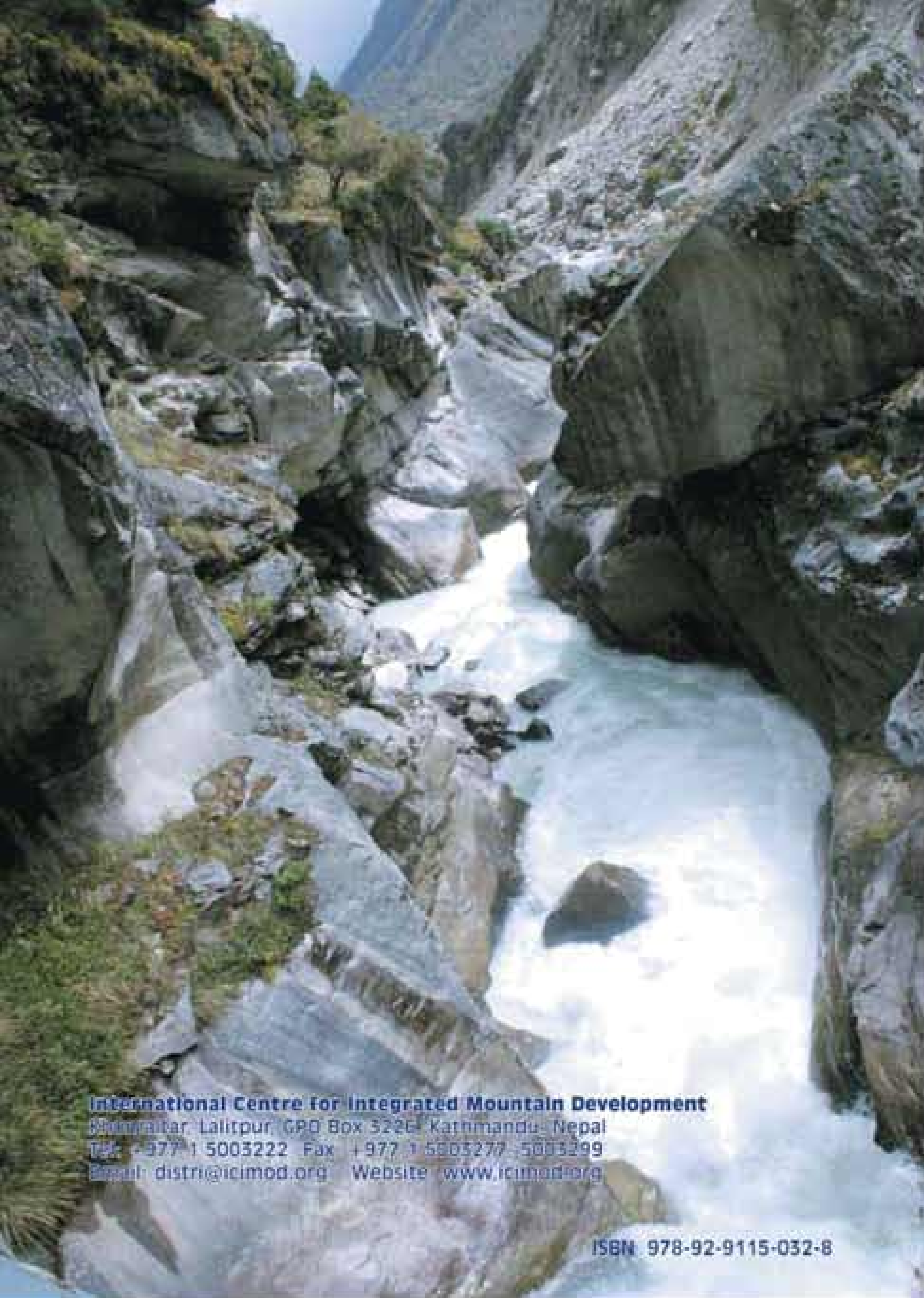
Xu Daoming (1985) Characteristics of Debris Flows Caused by Outbursts of Glacier Lakes in Boqu River in Xizang, China, 1981. In *Proceedings Debris Flow Symposium, Japan*, cited in WECS 1987

Yamada, T. (1998) *Glacier Lake and its Outburst Floods in Nepal Himalaya*, Data Centre for Glacier Research, Japanese Society of Snow and Ice, Monograph No. 1. Tokyo: Japanese Society of Snow and Ice

Yamada, T.; Shiraiwa, T.; Idia, H.; Kadota, T.; Watanabe, T.; Rana, B.; Ageta, Y.; Fushimi, H. (1992) 'Fluctuations of the Glaciers from 1970s to 1989 in the Khumbu, Shorong and Langtang Region, Nepal Himalayas'. In *Bulletin of Glacier Research*, 10: 11-19

Yamada, T.; Sakai, A.; Naito, N. (2003) 'On the Formation of a Moraine-dammed Glacier Lake in the Himalayas'. In *Proceedings on the 1st International Conference on Hydrology and Water Resources in Asia Pacific Region*, Vol. 1, pp 107-110. Bangkok: AIT

Yao, T. (2004) *Research and Environment News from China 2004*: China Daily, 23 September 2004



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