ICIMOD
FOR MOUNTAINS AND PEOPLE

Glacial Lakes and Glacial Lake Outburst Floods in Nepal

GFDRR
Global Facility for Disaster Reduction and Recovery

THE WORLD BANK

Note

This assessment of glacial lakes and glacial lake outburst flood (GLOF) risk in Nepal was conducted with the aim of developing recommendations for adaptation to, and mitigation of, GLOF hazards (potentially dangerous glacial lakes) in Nepal, and contributing to developing an overall strategy to address risks from GLOFs in the future. The assessment is also intended to provide information about GLOF risk assessment methodology for use in GLOF risk management in Nepal. The methodology that was developed and applied in the assessment can also be broadly applied throughout the Hindu Kush-Himalayan region. The assessment has been completed through activities carried out in collaboration with national partners, which include government and non-government institutions as well as academic institutions and universities.

This report was prepared by the following team:

- Pradeep K Mool, ICIMOD
- Pravin R Maskey, Ministry of Irrigation, Government of Nepal
- Achyuta Koirala, ICIMOD
- Sharad P Joshi, ICIMOD
- Wu Lizong, CAREERI
- Arun B Shrestha, ICIMOD
- Mats Eriksson, ICIMOD
- Binod Gurung, ICIMOD
- Bijaya Pokharel, Department of Hydrology and Meteorology, Government of Nepal
- Narendra R Khanal, Department of Geography, Tribhuvan University
- Suman Panthi, Department of Geology, Tribhuvan University
- Tirtha Adhikari, Department of Hydrology and Meteorology, Tribhuvan University
- Rijan B Kayastha, Kathmandu University
- Pawan Ghimire, Geographic Information Systems and Integrated Development Center
- Rajesh Thapa, ICIMOD
- Basanta Shrestha, Nepal Electricity Authority
- Sanjeev Shrestha, Nepal Electricity Authority
- Rajendra B Shrestha, ICIMOD

Substantive input was received from Professor Jack D Ives, Carleton University, Ottawa, Canada who reviewed the manuscript at different stages in the process, and Professor Andreas Kääb, University of Oslo, Norway who carried out the final technical review.

Glacial Lakes and Glacial Lake Outburst Floods in Nepal

International Centre for Integrated Mountain Development, Kathmandu, March 2011

This report was prepared by the International Centre for Integrated Mountain Development (ICIMOD) for the Global Facility for Disaster Reduction and Recovery (GFDRR)/ The World Bank.

Published by
International Centre for Integrated Mountain Development
GPO Box 3226, Kathmandu, Nepal

Copyright © 2011
International Centre for Integrated Mountain Development
Global Facility for Disaster Reduction and Recovery of the World Bank
All rights reserved. Published 2011

ISBN 978 92 9115 193 6 (printed)
978 92 9115 194 3 (electronic)

LCCN 2011-312004

Photos: All photos by Sharad P Joshi,
except p 55 (top) - Achyuta Koirala;
p 59 - Pravin R Maskey, p 80 Arun B Shrestha

Production team
Isabella Khadka (Consultant editor)
Greta Rana (Consultant editor)
A Beatrice Murray (Senior editor)
Dharma R Maharjan (Layout and design)
Asha Kaji Thaku (Editorial assistant)

Printed by Hill Side Press (P) Ltd., Kathmandu, Nepal

This publication may be reproduced in whole or in part and in any form for educational or non-profit purposes without special permission from the copyright holders, provided acknowledgement of the source is made. ICIMOD and the GFDRR Secretariat/World Bank would appreciate receiving a copy of any publication that uses this publication as a source. Copies may be sent to ICIMOD, GPO Box 3226, Kathmandu, Nepal and the GFDRR Secretariat at 1818 H Street NW. Washington, DC 20433 USA.

No use of this publication may be made for resale or for any other commercial purposes whatsoever without prior permission in writing from ICIMOD and the GFDRR Secretariat/World Bank. All images remain the sole property of the source and may not be used for any purposes without written permission from the source.

The views and interpretations in this publication are those of the author(s). They are not attributable to ICIMOD, GFDRR/The World Bank and do not imply the expression of any opinion concerning the legal status of any country, territory, city or area of its authorities, or concerning the delimitation of its frontiers or boundaries, or endorsement of any product.

This publication is available in electronic form at www.icimod.org/publications and www.gfdrr.org

Citation: ICIMOD (2011) *Glacial lakes and glacial lake outburst floods in Nepal*. Kathmandu: ICIMOD

Contents

Additional Material – DVD in back pocket

Dig Tsho on 24 April 2009; the GLOF event of 1985 caused more than 3 million dollars worth of damage and disrupted the downstream community for several months. The moraine dam was sufficiently destroyed that the reformed lake is no longer a threat.

Foreword

The Hindu Kush-Himalayan region contains the world's largest volume of glacier ice and perennial snow outside the polar regions. Its meltwater contributes to the major rivers that supply freshwater to almost a quarter of humanity residing in the downstream areas. Glaciers are sensitive indicators of increased air temperature. They have been studied extensively in many parts of the world as part of an international effort to improve understanding of the current pattern of global warming. Following the culmination of glacier advance during the Little Ice Age more than a hundred years ago, with short periods of reversal, glaciers have been thinning and retreating in many parts of the world. This process, in large part due to anthropogenic changes in the Earth's atmosphere, appears to have accelerated during the last few decades. The Hindu Kush-Himalayan region is no exception to the trend.

The Himalayan range extends for approximately 2,400 km within the 3,500 km length of the Hindu Kush-Himalayan ranges, and has about 33,000 sq.km of the estimated 110,000 sq.km of glaciated area. The Nepal Himalayas occupy 800 km of the central section of the Himalayan range.

Glacier thinning and retreat in the Himalayas has resulted in the formation of new glacial lakes and the enlargement of existing ones due to the accumulation of meltwater behind loosely consolidated end moraine dams that had formed when the glaciers attained their Little Ice Age maxima. Because such lakes are inherently unstable and subject to catastrophic drainage they are potential sources of danger to people and property in the valleys below them. The torrent of water and associated debris that sudden lake discharges produce is known as a glacial lake outburst flood (GLOF). Recent surveys have shown that many glacial lakes in Nepal are expanding at a considerable rate so that the danger they pose appears to be increasing. Nepal has experienced 24 GLOF events in the recent past, several of which have caused considerable damage and loss of life, for example, the Bhote Koshi Sun Koshi GLOFs of 1964 and 1981 and the Dig Tsho GLOF of 1985. The 1981 event damaged the only road link to China and disrupted transportation for several months, while the Dig Tsho GLOF destroyed the nearly completed Namche Small Hydroelectric Project, in addition to causing other damage farther downstream. The source of the former event was inside the Tibet Autonomous Region of China, indicating the necessity for international regional cooperation to address the dimension of the problem.

Glacial lakes, however, are not only sources of potential danger, they are also an important potential natural resource, which has yet to be effectively investigated. Monitoring glacier and water hazards, promoting community resilience and preparedness for disaster risk reduction, and ensuring the sharing of upstream-downstream benefits are priority areas in ICIMOD's programme. As glaciers and glacial lakes are related to both water resources and to water-related natural hazards, they need to be mapped and monitored to assess both their potential hazard and their resource value. ICIMOD has been involved in this type of endeavour since 1986.

The work reported here has received financial support from the World Bank. It is a systematic and comprehensive study of the status of glacial lakes in Nepal and an assessment of the hazard they pose and of the vulnerability of downstream people and property. It begins with the actual mapping of glacial lakes. This is followed by a hazard assessment. Next the problem of determining the most dangerous of the lakes is addressed, accompanied by analysis of the degree of downstream vulnerability. The report concludes by proposing some preliminary steps for development of a national strategy for response to the hazard, and emphasising the need for applying the experience obtained towards initiation of a region-wide international response. In this regard, on behalf of ICIMOD, I would like to thank the World Bank for its vital financial contribution. I would also like to thank the Swedish International Development Cooperation Agency (Sida) and the Norwegian Ministry of Foreign Affairs for additional financial support.

Andreas Schild
Director General, ICIMOD

Acknowledgements

The successful implementation of this project was made possible through cooperation between the World Bank and ICIMOD. Financial assistance provided by the World Bank is gratefully acknowledged. Additional financial support from the Swedish International Development Cooperation Agency (Sida) and from the Norwegian Ministry of Foreign Affairs for some of the project activities is also gratefully acknowledged. The authors would like to express their thanks to Dr Andreas Schild (ICIMOD Director General) for his continued support to this project; to Dr Madhav B Karki (ICIMOD Deputy Director General); Dr Eklabya Sharma (ICIMOD Director Programme Operations); Mr Berend de Groot (former ICIMOD Director Programme Operations); and Professor Hua Ouyang (ICIMOD Programme Manager Integrated Water and Hazard Management) for their support and guidance throughout.

This work benefited from collaboration with partner institutes and these are highly appreciated. We would like to express our heartfelt thanks to all the partner institutes and their representatives, especially Mr Om R Bajracharya (Department of Hydrology and Meteorology, Government of Nepal), Dr Megh R Dhital (Department of Geology, Tribhuvan University), and Professor Lochan P Devkota (Department of Hydrology and Meteorology, Tribhuvan University), for their continued cooperation and support. Sincere thanks also go to Mr Gautam Rajkarnikar, Water and Energy Commission Secretariat (WECS); Mr Khom Raj Dahal and Mr Shreekamal Dwivedi, Department of Water Induced Disaster Prevention (DWIDP); Mr Sagar Mishra, Ministry of Home Affairs (MoHA), Government of Nepal; and Professor Panna Thapa, Kathmandu University (KU).

We would also like to acknowledge the contributions of Dr Shyam S Ranjitkar (Sr Irrigation Engineer, World Bank, Nepal Country Office, Kathmandu) who coordinated the project on behalf of the World Bank, Mr Saurabh Dani (GFDRR, South Asia/World Bank), and Mr Christoph Pusch (World Bank - South Asia Region). Likewise, the constant help of Ms Tara Shrestha (Team Assistant) and Ms Silva Shrestha (Research Analyst) at the World Bank Nepal Country Office, Kathmandu was much appreciated.

The authors would like to thank the ICIMOD editorial team of Dr A Beatrice Murray (Head Communications Division), Dr Isabella Khadka and Ms Greta Pennington Rana (consultant editors), Mr Dharma R Maharjan (layout and design), and Mr Asha Kaji Thaku (cartography and design support) for their help in bringing the publication to its final form.

During the field investigation at Imja Tsho on 12 May 2009, one of the team members, Mr Suresh Maharjan, lost his life. The authors would like to pay a special tribute to him; his hard work and enthusiastic team spirit were substantial contributions to the field investigation and he is sadly missed. We hope that the addition of knowledge to this field will be a tribute to his commitment.

Critical comments and suggestions received from Dr Golam Rasul, Head, Economic Analysis Division, ICIMOD, on the vulnerability assessment and GLOF risk management strategy sections of the report is much appreciated. Last but not least, the authors extend their sincere appreciation to Professor Jack D Ives of Carleton University, Canada for his detailed review and substantive input to the report at different stages, and Professor Dr Andreas Kääb, Department of Geosciences, University of Oslo, Norway for critically reviewing the report and sharing his insights and comments.

Executive Summary

The world's climate has been warming for more than a hundred years: there have been fluctuations, notably cooling phases in the 1960s and 1970s, although long-term records indicate an accelerating warming trend from about 1980. Although this has influenced ecosystems worldwide, its effects on glaciers and the duration of winter snow cover have been particularly noticeable, especially in the European Alps and Greenland, and on the reduction of sea ice cover in the Arctic Ocean. The Hindu Kush-Himalayan region has been no exception.

One of the more spectacular effects of recent atmospheric warming in the Himalayas has been the creation of meltwater lakes on the lower sections of many glaciers. In an increasing number of instances, especially well-documented in Nepal, several of these lakes have burst their natural retaining dams (usually old end moraines that were formed when the glaciers were thicker and more extensive than today). This has produced catastrophic flood surges (glacial lake outburst floods or GLOFs) that have destroyed infrastructure and taken human lives in the valleys below.

Fourteen GLOF events have been recorded in Nepal in recent decades; several others in Tibet Autonomous Region in China have crossed the international border to cause extensive damage in Nepal. Other GLOFs have been recorded across the Hindu Kush-Himalayan region.

Systematic application of remote sensing and air photo interpretation has shown that many hundreds of glacial lakes have formed in recent years, while others have enlarged, on occasion to lengths exceeding two kilometres with depths approaching a hundred metres. In this way, immense volumes of meltwater have accumulated behind potentially unstable moraine dams. There is no doubt that people and property for considerable distances downstream from the unstable lakes are facing a serious threat to their existence: the problem, however, is how to determine the degree of probability of such an event.

This situation, together with the realisation that the risk of damage and loss of life may continue to increase in the near future, has prompted the preparation of the present report. Its intent is to assess the current degree of risk, to determine the extent of vulnerability of people and property to the potential outburst of glacial lakes, and to provide a basis for strategy development to help ensure a timely response.

The report is based upon information and experience accumulated during collaboration with several partner institutions in Nepal. It outlines a stepwise approach to assessment of risk beginning with an extensive desk study of aerial photographs and satellite images that provided the first reconnaissance mapping of more than a thousand glacial lakes. There followed a provisional identification of six lakes that were considered to be potentially dangerous and that warranted special study. Three lakes, namely, Tsho Rolpa, Thulagi Lake, and Imja Tsho, were selected for detailed field investigation, application of computer dam-break modelling, and assessment of the vulnerability of human life and property for up to 100 kilometres downstream.

Analysis of the rapidly growing worldwide literature on the outburst of glacial lakes, and the project's field and theoretical experience, have led to the conclusion that it is not feasible to make a reliable prediction of a specific occurrence on the basis of our existing knowledge. The difficulty involved in any attempt to forecast danger is emphasised. Concomitantly, it is proposed that news media and other sources in recent years have perpetrated highly exaggerated claims of imminent large-scale catastrophe, and that this is in itself counter-productive and should be contested. Nevertheless, while the danger has been heavily distorted, GLOFs may occur in future, or even tomorrow (although spurious accuracy in assessment of probability is considered unhelpful). As direct predictions cannot be made, there is an urgent need to monitor a careful selection of prioritised lakes on a regular basis. This should be carried out in collaboration with other institutions, both nationally and internationally.

In view of the uncertainties facing the refinement of a 'probability index', Tsho Rolpa and Imja Tsho have been identified for continued and more intensive study. This will require both geophysical field investigation and more exacting downstream vulnerability assessments. The latter should involve generation of local awareness and incorporation of downstream populations and managers of large-scale infrastructure (such as hydroelectricity projects) into the observation of targeted lakes, and evaluation of early warning systems, and their possible installation: further refinement of dam-break modelling, as an essential part of vulnerability assessment, should be undertaken.

It is also recommended that ICIMOD develop an exhaustive archive for all relevant data: field data; satellite imagery; ground photographs; and all available scientific and technical reports and publications. A final and overriding recommendation is that the data and experience acquired during the formulation of this report be used as a basis for the development of a national strategy aimed at risk reduction. A draft outline of the elements for such a strategy is provided as part of this report.

Region-wide cooperation throughout the Hindu Kush-Himalayas should follow, and it is recommended that steps be taken to organise a region-wide planning session for experts and leaders of relevant national institutions to develop a more coordinated approach and begin laying the foundations for a glacial lake outburst risk reduction policy.

Section 1

Introduction to the Study

Imja Tsho with Mt. Ambulapcha in the background, 14 October 2010

1 Introduction

Background

For as long as historic records have been available, evidence has been documented that glaciers and glacial lakes have been a hazard to people and property located downstream. During the so-called 'Little Ice Age' (about AD 1500 – 1900), glaciers thickened and advanced and, in many instances, blocked side valleys causing river and meltwater to accumulate against an ice barrier. In some instances, as these glacial lakes grew, increasing hydrostatic pressure eventually caused the ice dam to lift or burst. In other instances, the lake level simply rose to overtop the ice dam. In either case, when the lake drained, either partially or entirely, the water which was released suddenly was destructive to anything in its path. This phenomenon was repeated at intervals as the glacier dam re-formed following the outbreak.

In regions such as the European Alps, Scandinavia, and Iceland such catastrophic events have been recorded for several hundred years, often in great detail. Comparable disasters have doubtlessly occurred in other mountain areas where they were either not recorded, or took place in areas that were uninhabited. Such hitherto unrecorded major events are now being detected by modern geo-scientific research.

The sudden drainage of ice-dammed lakes attracted scientific interest from the mid-19th century as the natural sciences developed rapidly. Some of the earliest attempts to relate such events to atmospheric warming and sea-level rise (post-Little Ice Age) were undertaken by Swedish and Icelandic scientists and this gave rise to the colloquial Icelandic term 'jökulhlaup' (glacier leap) entering the scientific literature (Thorarinsson 1939; Ahlmann 1948). Another, even more dramatic, form of glacier outburst which results from sub-glacial volcanic activity is also common in Iceland (Thorarinsson 1953; Björnsson 2009a, 2009b). Individual historic events (for example, the 1727 eruption of Öraefajökull), in conjunction with peak glacial activity during the Little Ice Age, were sufficiently catastrophic to threaten the very existence of Iceland.

After the mid-19th century, the world climate began to change. The maximum advance of glaciers occurred at different times in different parts of the world, ranging from the early 19th century to as recently as 1905. After this time, mountain glaciers globally began to experience overall thinning and retreat, with several decadal reversals and regional contrasts. This behaviour of glaciers so intrigued scientists that in the first half of the 20th century individual glaciers were selected for continuous annual mass balance and climatological study: included were several glaciers in Europe such as the Kårsa glacier in Arctic Sweden (Wallén 1949); somewhat later, the Peyto glacier in the Canadian Rockies (Østrem 1966, 2006; Østrem and Brugman 1991); and others in the Canadian High Arctic (Axel Heiberg Island, Fritz Müller). Fritz Müller's world glaciological vision led to the establishment of the International Inventory of Glaciers (Müller et al. 1977).

Many studies which systematically record glacier terminal positions have been carried out annually without a break until the present day. This large and growing bank of data provides vital information for critical determination of the impacts of current climate change. It is universally recognised by glaciologists and climatologists, however, that the number of 'indicator' glaciers is very small and that many mountain ranges have no adequate representative data sets. Furthermore, observations that are restricted to an annual recording of the position of glacier termini provide a very limited tool.

As a result of the fact that the world's glaciers are at present thinning and retreating, associated meltwater lakes are increasing in size and new lakes continue to be created. These lakes differ from the ice-dammed lakes which attracted scientific attention earlier, because they are predominantly supra-glacial and moraine-dammed rather than dammed by advancing glaciers. This type of lake is characteristic of many of the glacial lakes found in the Himalayas and they constitute the major topic of this report.

Despite the lack of systematic glaciological and climatological research, since the 1970s it has become increasingly apparent that, although there are conspicuous exceptions, the majority of glaciers throughout the Hindu Kush-Himalayan region have been thinning and retreating. Today it is generally accepted that this is a consequence of the atmospheric warming that is affecting glaciers worldwide. It is important to note, however, that overly close comparisons between the response of Himalayan glaciers and those in the European Alps, where long-term data sets are available, are not always productive. The major differences between the two types of glaciers are (1) the extremely high altitude of the glacial region of the Hindu Kush-Himalayas; (2) many of the longer glacier tongues are mantled by a heavy cover of rock debris for several kilometres upstream of their termini and have very low gradients – these characteristics are very significant in terms of glacial mass balance and the manner of wasting; (3) knowledge about the meso-scale and local (micro-scale) climatology of glacial environments is inadequate due to the scarcity of data from high-altitude meteorological and hydrological observations; and (4) despite a large amount of selective glaciological research, there are virtually no systematic, long-term records of mass balance in the Hindu Kush-Himalayan region.

Supra-glacial lakes often appear to merge with moraine-dammed lakes, or may develop contemporaneously as composite forms. In addition, their end moraines may be underlain by masses of dead ice which are remnants of earlier glacial expansion. Permafrost may also be present. Buried dead ice and permafrost strengthen the end moraines and reduce the risk of glacial lake outbursts to a great extent. Nevertheless, the current atmospheric warming also affects buried ice and permafrost. In any event, as these lakes increase in size and deepen, the presence of open water in contact with the glacier terminus further accelerates glacial retreat and thinning and may give rise to increasing instability.

Meltwater lakes are potentially unstable; the sudden catastrophic release of water from such a lake is known as a glacial lake outburst flood (GLOF). In Nepal, little attention was paid to this phenomenon until the sudden outburst of the Dig Tsho (Tsho = lake), a glacial lake in the western section of the Sagarmatha (Mt Everest) National Park, Khumbu Himal, on the 4th August, 1985.

When the end moraine dam of the Dig Tsho collapsed, the water from the lake drained into the valley downstream over a four-hour period, wreaking destruction as it went. This sudden outburst destroyed the nearly completed Namche Small Hydel facility, some 11 km downstream and caused other losses as far as 50 to 60 km downstream. Somewhat ironically, Dig Tsho was not typical of the large glacial lakes that have formed supra-glacially, but was one of the smaller 'clean-ice' glacial lakes. The outburst event was triggered by a large ice and rock avalanche that cascaded into the lake from a steep glacial surface: when it splashed into the lake it produced a surge wave. The surge overtopped the end moraine and caused it to collapse, discharging an estimated 6 - 10 million cubic metres of water into the valley below. The outbreak of Dig Tsho caused more than three million dollars worth of damage and disrupted the downstream community of Khumbu for several months. The alarm bells sounded by this outburst event put in motion a plethora of scientific investigations, including, surveys, research, and preliminary estimates of downstream vulnerability among others. The Water and Energy Commission Secretariat (WECS) of the Nepal Government, the International Centre for Integrated Mountain Development (ICIMOD), and the United Nations University (UNU) collaborated in the work that eventually produced the first detailed assessment of a GLOF event in Nepal (WECS internal report 1987; Ives 1986; Vuichard and Zimmermann 1986, 1987).

The Dig Tsho event showed that it is not necessarily the largest lakes that are the most dangerous, and that even small lakes may cause serious damage, especially if there are populated areas and infrastructure located near the hazard source. In the decade after 2000, several outburst floods from small lakes were reported in the western part of the Teskey Ala-Too range, Tien Shan, Kyrgyzstan. In this region most glacial lakes are small. For example, Zyndan Lake in the Tong District of Ysyk-Köl Oblast, Kyrgyzstan, formed rapidly over two and half months (from early May to late July 2008), and with an area of only 0.0422 sq.km, burst on 24 July. The GLOF from this small lake killed three people and numerous livestock, destroyed infrastructure, and devastated potato and barley crops as well as pastures (Narama et al. 2010). Such disasters highlight the fact that the downstream vulnerability might be as important, or more important, than the actual volume of water released.

After the initial flurry of scientific activity that immediately followed the Dig Tsho event, there was a partial hiatus in GLOF-related investigations in Nepal until the late 1990s, when it was noticed that Tsho Rolpa, a large glacial lake at the terminus of the Trakarding glacier in Rolwaling Himal could be close to overtopping and destabilising its end moraine. This led to mitigation efforts that included the construction of an artificially reinforced channel which was cut through the end moraine to allow the level of the lake to be lowered by three metres (Rana et al. 2000, Richardson and Reynolds 2000). This also marked the beginning of a determined response to the threat of GLOF activity in Nepal.

Other, non-structural measures, such as remote sensing, were started and led to region-wide identification and mapping of the glaciers and glacial lakes that seemed to be forming in large numbers (Mool et al. 2001a; 2001b). At the outset, this work focused on Nepal and Bhutan. Subsequent work in collaboration with various institutions within ICIMOD's member countries led to completion of a preliminary inspection of the entire Hindu Kush-Himalayan region (Mool and Bajracharya 2003; Bhagat et al. 2004; Sah et al. 2005; Roohi et al. 2005; Wu Lizong et al. 2005).

In a next step, supported by The World Bank Global Facility for Disaster Reduction and Recovery (GFDRR), and with additional support from the Swedish International Development Cooperation Agency (Sida) and the Norwegian Ministry of Foreign Affairs, a detailed multistep risk assessment methodology for glacial lakes was developed and used in collaboration with national partners to assess the hazard posed by glacial lakes in Nepal. This publication provides a detailed account of the results of the study; additional material, including the GIS database, is provided on a DVD included in the back pocket. Some preliminary results were also provided in Ives et al. (2010).

Objectives of the Study

The present study had two main objectives:

1. to develop recommendations for adaptation to, and mitigation of, GLOF hazards in Nepal, concentrating on a small number of lakes perceived as especially critical, and
2. to assist the Government of Nepal in developing an overall strategy to address possible risks from GLOFs in the future.

This two-fold objective requires both an assessment of the extent to which specific glacial lakes are unstable, and an analysis of the degree to which people and property downstream are vulnerable. The overall approach requires strengthening of partnerships among key stakeholders including local people, major private and community corporations, government agencies, non-government organisations (NGOs), and tourist-oriented businesses, among others. This work will contribute to the development of an overall strategy for GLOF risk management which will include a more precise identification of the hazard as well as early warning and mitigation measures. As the physical attributes of glacial lakes are similar throughout the Hindu Kush-Himalayas, it is hoped that the results of this work can also be applied to other parts of the region.

GLOF Risk Assessment Methodology

A step by step approach has been developed and applied for GLOF risk assessment. A schematic representation of the methodology of this approach is shown in Figure1.1. It begins with the mapping of glacial lakes and the study of the existing inventory.

Once the glacial lakes are mapped, they are then identified as either potentially dangerous or not, based on a set of defined criteria. The labelling of the lakes at this step does not include categorising the vulnerability of the downstream areas.

The next step involves ranking of the potentially dangerous lakes and setting of priorities for further detailed investigation. For this, the physical condition of a lake related to its stability is assessed by taking into consideration its area, the characteristics of the associated glacier, any changes in boundary conditions, and the stability of the surrounding terrain. Downstream socioeconomic parameters must also be obtained (Figure 1.1).

Socioeconomic parameters include settlements, the number and type of bridges and roads, number and capacity of hydropower projects and the distances to these, the area of agricultural land, location of other important infrastructure, and any other activities of economic value. Repeated observation from low-flying aircraft is a rapid reconnaissance tool which provides an overview of changes and assists in the identification of vulnerable settlements and infrastructure to help assign priority to areas at the hydrological basin level. Thus, aerial observation is an important step in the ranking of potentially dangerous lakes.

After ranking, typically only a few lakes will be given high priority for detailed follow-up investigation through either desk-based or field studies.

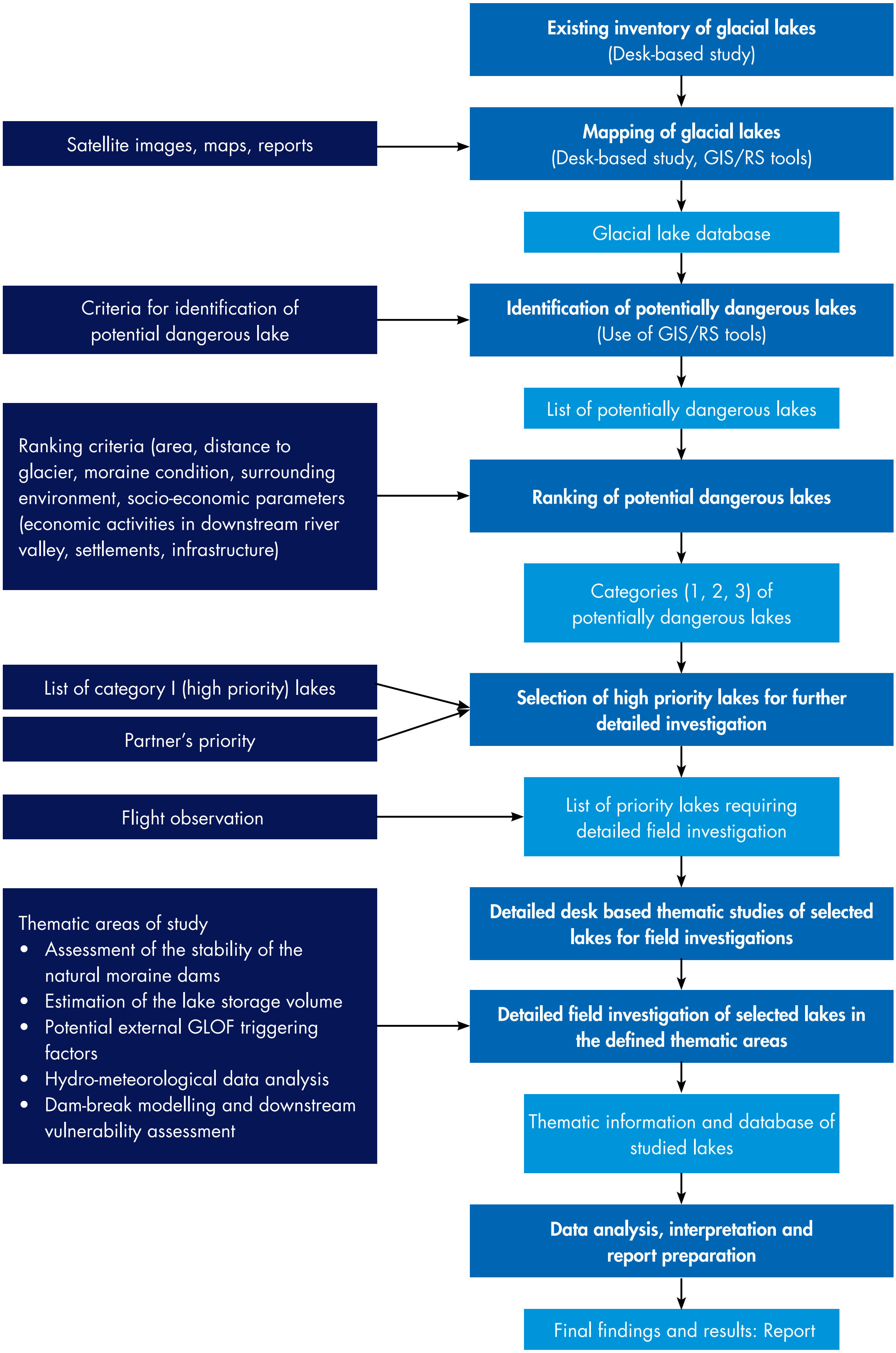


Figure 1.1: **Flow diagram of the step-by-step approach for GLOF risk assessment**

The next step in the risk assessment is the desk-based study of the high-priority lakes selected in order to identify the data gaps and any specific characteristics to be emphasised during the following field study.

The detailed field investigation should focus mainly on the following aspects: estimation of the stability of natural moraine dams; determination of a lake's storage capacity; potential external triggering factors; hydrometeorological data analysis; modelling a potential dam outburst; and carrying out a downstream vulnerability assessment. For overall GLOF risk management, the magnitude of the hazard is directly related to the downstream vulnerability appraisal (Figure 1.1).

Analysis and interpretation of the results obtained from these studies should lead to improved understanding of the overall physical and socioeconomic risks from a GLOF. This will enable recommendations to be formulated for GLOF hazard management and risk mitigation measures.

Design of the Nepal Study

In order to fulfil the objectives outlined above, the step-by-step methodology was applied systematically in collaboration with partners including institutes of the Government of Nepal, academic institutions, international organisations, and other key stakeholders. A Steering Committee was formed on 5 November 2008 to provide overall guidance and support for the project with representatives from Nepal's Department of Hydrology and Meteorology (DHM), Department of Water Induced Disaster Prevention (DWIDP), the Ministry of Home Affairs (MoHA), the Water and Energy Commission Secretariat (WECS), and ICIMOD. An inception workshop was held on 12 November 2008 to formulate the detailed project activity plan. The workshop was attended by representatives of government organisations, academic institutions, international NGOs (INGOs), and private institutes.

As an integral part of the investigation, several workshops and consultative meetings were organised at ICIMOD in Kathmandu. This ensured guidance for project implementation, field planning, and acquisition of equipment, as well as for dissemination of the findings from the field investigations. It also provided guidance for development of a strategy for GLOF risk management. Three workshops were held in the corresponding districts of the three lakes selected for intensive study in order to share information derived from the field investigations. This proved an effective arrangement for obtaining feedback from local communities and stakeholders. Similarly, two national workshops were organised at ICIMOD in order to facilitate dissemination of information on the project progress. The open discussions that ensued served to enhance project performance. Feedback was also obtained from various experts.

Specialised members from partner institutions participated in the field investigations and contributed to the preparation of the technical reports. This helped to reinforce the capacities of the Nepalese institutions. Dissemination of the experience and information gathered during the field investigations to stakeholders, partner institutions, and local communities through a series of workshops and seminars helped to create awareness not only at the grass roots level but also among local government organisations and other stakeholders. Interaction with local communities and local government organisations, such as the district development committees, also helped to create an awareness of the project's findings and draw attention to the fact that glacial lakes also constitute a potential natural resource that should be incorporated into local land-use planning.

The present report was prepared as the final step, summarising different aspects of the findings of the project and the wider implications for dissemination to a broad audience. The report contains a summary of the information on mapping of glacial lakes, databases, field-based investigation information, and issues related to GLOF monitoring, early warning, and mitigation. It also includes general guidelines for the formulation of a strategy with regards to GLOF risk management. With the involvement of the appropriate regional partners, it is hoped that the methodology developed and applied in this project can be extended to similar GLOF-prone areas in other parts of the Hindu Kush-Himalayan region.

Dudh Koshi below Imja lake showing remains of damage from the Nare GLOF event in 1977 and Pangboche village on the right bank of the river, 24 April 2009

2 Glacial Lake Outburst Floods in Nepal

Characteristics

There are two distinctly different forms of glacial lake outbursts: those that result from the collapse or overtopping of ice dams formed by the glacier itself, and those that occur when water drains rapidly from lakes formed either on the lower surface of glaciers (supra-glacial) or between the end moraine and the terminus of a retreating glacier (moraine-dammed). At present, supra-glacial and moraine-dammed lakes are far more common in the Hindu Kush-Himalayan region than glacier-dammed lakes as their development is favoured by the overall atmospheric warming and glacier wastage. Nevertheless, ice-dammed lakes are also present in the region and warrant close attention. Investigations show that the phenomenon of ice-dammed lakes is largely confined to parts of the Karakoram Mountains in northern Pakistan where their existence is related to (perhaps anomalously) advancing glaciers. In Nepal, these forms of ice-dammed lakes are either only present in very small numbers if at all, or their existence has escaped notice. The present study includes both the larger supra-glacial lakes and those that have formed between the end moraines and termini of glaciers.

GLOF Events Affecting Nepal

According to the information available, Nepal has experienced at least 24 GLOF events in the past. Of these, 14 are believed to have occurred in Nepal itself, and 10 were the result of flood surge overspills across the China (Tibet AR)-Nepal border (Figure 2.1, Table 2.1). Geomorphological field data suggest that the earliest of these occurred some 450 years ago and that it swept down the Seti Khola (river) valley from the upper basin on the north side of Mt Machhapuchchhre (Fort 1987; Fort and Freytet 1983; Carson 1985). This GLOF would have been of very high magnitude to account for the deposition of debris to depths of between 50 and 60 metres across wide areas of the Pokhara Valley. While this event is not particularly relevant to the present report, it is mentioned, both for the record, and to emphasise the fact that various forms of high magnitude-low frequency events are an integral part of the high-altitude mountain environment. As Kenneth Hewitt (1997) remarked: "Mountainous terrain is a dangerous environment for human occupation."

Among the 14 GLOF events known to have occurred in Nepal, one took place in the distant past; five of recent date are quite well recorded; and eight of indeterminate date and two of recent date were recorded as occurrences, but without details of the losses incurred.

Specific GLOF Events

Short descriptions of the known past GLOF events are given below in chronological order: first those that occurred entirely within Nepal; followed by those that originated in the Tibet AR, and then flowed downstream into Nepal (Mool et al. 2001a; Bajracharya et al. 2008; Ives et al. 2010).

Originated in Nepal

Seti Khola (date unknown – approximately 450 years ago)

Geomorphological investigations indicate that the origin of an enormous debris deposit across the Pokhara Valley was a very high magnitude event, probably a GLOF from the north side of Mt Machhapuchchhre. No details of the actual damage sustained are available but it is assumed that it was very great.

Figure 2.1: **Location of GLOF events recorded in Nepal, and in Tibet AR, China, that caused damage in Nepal**

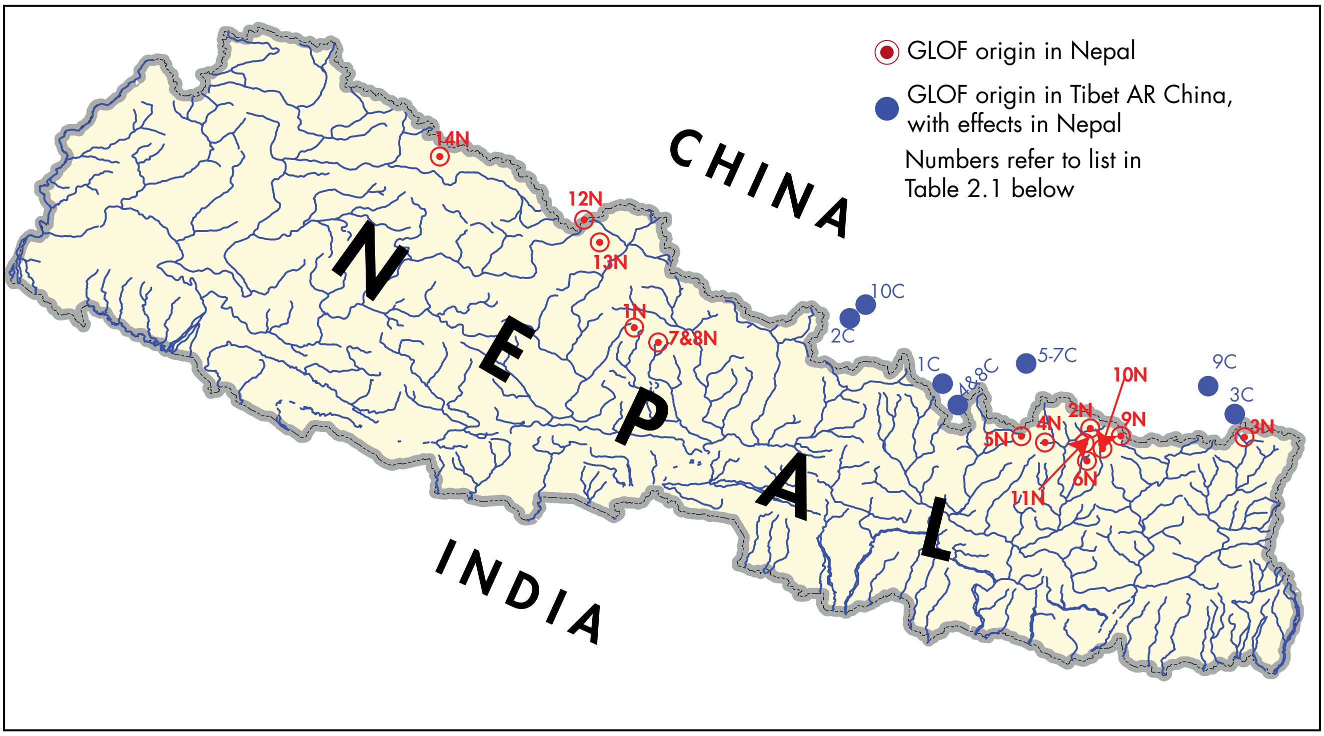


Table 2.1: **GLOF events recorded in Nepal**
(after Mool et al. 1995, 2001a; Yamada 1998a; Bajracharya et al. 2008; Ives et al. 2010)

	Date	River basin	Lake	Cause	Losses
Entirely within Nepal					
1N	450 years ago	Seti Khola	Machhapuchchhre	Moraine collapse	Pokhara valley covered by 50–60m deep debris
2N	3 Sep 77	Dudh Koshi	Nare	Moraine collapse	Human lives, bridges, others
3N	23 Jun 80	Tamor	Nagma Pokhari	Moraine collapse	Villages destroyed 71 km from source
4N	4 Aug 85	Dudh Koshi	Dig Tsho	Ice avalanche	Human lives, hydropower station, 14 bridges, etc
5N	12 Jul 91	Tama Koshi	Chubung	Moraine collapse	Houses, farmland, etc.
6N	3 Sep 98	Dudh Koshi	Tam Pokhari	Ice avalanche	Human lives and more than NRs 156 million
7N	15 Aug 03	Madi River	Kabache Lake	Moraine collapse	Not known
8N	8 Aug 04	Madi River	Kabache Lake	Moraine collapse	Not known
9N	Unknown	Arun	Barun Khola	Moraine collapse	Not known
10N	Unknown	Arun	Barun Khola	Moraine collapse	Not known
11N	Unknown	Dudh Koshi	Chokarma Cho	Moraine collapse	Not known
12N	Unknown	Kali Gandaki	Unnamed (Mustang)	Moraine collapse	Not known
13N	Unknown	Kali Gandaki	Unnamed (Mustang)	Moraine collapse	Not known
14N	Unknown	Mugu Karnali	Unnamed (Mugu Karnali)	Moraine collapse	Not known
Originated in TAR/China and caused damage in Nepal					
1C	Aug 1935	Sun Koshi	Tara-Cho	Piping	66,700 sq.m of wheat fields, livestock, etc
2C	25 Aug 64	Trishuli	Longda	Not known	Not known
3C	21 Sep 64	Arun	Gelhaipuco	Glacier surge	Highway and 12 trucks
4C	1964	Sun Koshi	Zhangzangbo	Piping	No remarkable damage
5C	1968	Arun	Ayaco	Not known	Road, bridges, etc
6C	1969	Arun	Ayaco	Not known	Not known
7C	1970	Arun	Ayaco	Not known	Not known
8C	11 Jul 81	Sun Koshi	Zhangzangbo	Ice Avalanche	Hydropower station
9C	27 Aug 82	Arun	Jinco	Glacier surge	Livestock, farmland
10C	6 Jun 95	Trishuli	Zanaco	Not known	Not known

Dudh Koshi (3 September 1977 – Nare Lake)

This event was investigated by Buchroither et al. (1982) based on digital processing of Landsat MSS satellite data. Fushimi et al. (1985) also provided a detailed account. However, there is some disagreement between the two about both the cause and manner of the actual outburst and the total volume of water released. It appears that a relatively small glacial lake located at a higher elevation discharged into Nare Lake, located below the peak of Mt Ama Dablam. The rapid inflow of water caused Nare Lake to overtop its end-moraine dam and discharge into the Imja Khola (river) and thereafter down the Dudh Koshi valley. The government's hydrological recording gauge at Rabuwa Bazar, 90 km downstream from the source, showed a prominent discharge peak on 3 September 1977. Nevertheless, this attenuated GLOF discharge peak was far below those recorded on the 26th, 27th, and 28th August 1977, due to 'normal' summer monsoon peak floods.

Fushimi et al. (1985) estimated that 4×10^5 cubic metres of water were released from Nare Lake; Buchroither et al. (1982) estimated a total discharge of 5×10^5 cubic metres, with a peak discharge of 800 cumecs. Two or three lives were lost, all the bridges for 35 km downstream were destroyed, and the flood wave triggered debris flows from the valley slopes. There were other material losses. When the United Nations University (UNU) mountain hazard mapping reconnaissance group walked from Lukla to Namche in March 1979, evidence of the effects of the GLOF were still clearly visible where the Dudh Koshi valley infill of debris deposits had been washed away leaving low terraces with unstable cliffs on parts of the valley walls. When the UNU team made a 1:50,000 scale mountain hazards map (Zimmermann et al. 1986), they concluded that, apart from high magnitude very low frequency events (very low probability and not yielding to prediction) (Heuberger et al. 1984), the most serious threat facing the people of the Khumbu Himal was that of another possible glacial lake outburst.

Tamor (23 June 1980 – Nagma Pokhari)

A GLOF event in the Tamor basin occurred due to the collapse of a moraine in the Nagma Pokhari basin and destroyed villages as far as 71 km downstream from the outburst. This lake has since reformed to a critical level and is thus included in the potentially dangerous category.

Dudh Koshi (4 August 1985 – Dig Tsho)

The Dig Tsho GLOF is the most thoroughly documented event of its type in Nepal (WECS 1987; Ives 1986; Vuichard and Zimmermann 1986, 1987). Thus only the most salient points are discussed here in a little more detail.

The Dig Tsho is a glacial lake dammed by the end moraine of the Langmoche Glacier in the western section of Sagarmatha (Mt Everest) National Park. The glacial meltwater drains from Dig Tsho into the Bhote Koshi river, a main tributary of the Dudh Koshi in the Khumbu region. The catastrophic drainage of Dig Tsho marked a turning point in the study of potentially dangerous glacial lakes in Nepal and possibly for the entire Himalayan region. This is partly because of the extent of the damage it caused when it obliterated the nearly completed Namche Small Hydel facility located 11 km from the breach, caused damage for tens of kilometres downstream, and resulted in the loss of four or five lives. Perhaps of equal importance was the fact that it also destroyed long sections of the main trekking route to the Mt Everest base camp. The GLOF event occurred in August during the summer monsoon hiatus in the trekking season, but had the timing been different, several hundred lives might have been at risk (trekkers, guides, and porters). Likewise, had the event coincided with the weekly Namche market that draws large numbers of traders and porters, the loss of life might have been greater still. Extensive geomorphological details and first-hand local interviews were obtained by Vuichard and Zimmermann, in large part because the UNU mountain hazard mapping project was able to support a field investigation immediately following the event. Zimmermann had actually photographed Dig Tsho and the Langmoche Glacier end moraines in September 1982. This enabled Vuichard to obtain a replicate photograph in September 1985 (Ives 1986: Plates 6 and 7; Vuichard and Zimmermann 1987). Dr Victor Galay, as consultant to WECS, also obtained outstanding photographs both before and after the event (reproduced in Ives 1986).

The Langmoche Glacier slopes steeply into its frontal lake. It is a 'clean-ice' glacier, with little or no surface debris, surrounded by precipitous mountain walls and hanging glaciers. The GLOF event appears to have been triggered by an ice avalanche (possibly accompanied by rock fall) that hit the steep glacier surface and fell suddenly into the lake. The lake had been close to topping its end-moraine dam for at least three years previous to the event. It was inevitable that a large surge wave would eventually wash over the dam at its lowest point and cut a channel across it. This instantaneous increase in the volume of water rapidly overflowing the end moraine acted to sever it. In fact, the breach was complete.

Vuichard and Zimmermann (1986, 1987) estimated that 6–10 million cubic metres of water drained from the lake in about four hours, making the average rate of discharge about 500 cumecs. They estimated an actual peak discharge of water as high as 2,000 cumecs. From accounts given by local eye witnesses, it appears that there were two or more distinct surges because the bridge at Jubing, 40 km downstream from the source, washed out 90 minutes after the initial flood wave had passed. Another factor that increased the destructive power of this GLOF was the fact that the flood waters incorporated debris from the moraine breach and additional loose deposits, which included material from locally-induced debris flows from the valley sides that were equal in volume to that of the surging water. The volume and rate of flow of the turbulent mix of water and debris varied from point to point as a result of variations in the width and steepness of the valley. Although the original estimates have been revised somewhat since, they provide an adequate 'order of magnitude' for the scale of the event. A final point is that because of the unstable nature of many sections of the valley walls landslides and general instability caused many problems, including loss of life, for several months after the initial event. After the August 1985 drainage of Dig Tsho, the lake partially re-formed, but because the breach in the end moraine was so complete, it ensured a low-level outlet of meltwater and the lake is no longer considered to be dangerous.

One of the more significant results of the immediate investigation of the Dig Tsho GLOF was that it prompted cooperation between WECS, ICIMOD, and UNU to extend examination of the hazard and marked the beginning of a systematic attempt to identify other critical lakes in the Khumbu and surrounding areas.

Tama Koshi (12 July 1991 – Chubung Lake)

Chubung Lake discharged when its end-moraine dam collapsed. Few details are available although it is known that some houses were destroyed and some farmland was torn away.

Dudh Koshi (3 September, 1998 – Tam Pokhari Lake)

This GLOF was triggered when an ice avalanche hit the frontal lake and induced a surge wave which overtopped the end moraine dam. There is a brief report which indicates that lives were lost and that NRs 156 million in damage was incurred (about 2 million US$) (Dwivedi et al. 1999).

Madi River (15 August 2003 and 8 August 2004 – Kabache Lake)

Two GLOF events occurred in two consecutive years on almost the same date on the Madi River from Kabache lake as a result of moraine collapse: details of the damage are not known.

Others

In addition to the events described above, six GLOFs have been identified in Nepal from analysis of geomorphological features seen on satellite images and aerial photographs. Precise dates and details of the events are not available, however all are known to have occurred when the end moraines collapsed. Two events were identified in the Arun basin (Barun Khola); one in the Dudh Koshi (Chokarma Cho); two in Mustang (Kali Gandaki); and one in the Mugu Karnali.

Originated in TAR/China and caused damage in Nepal

Between1935 and 1995, there are records of ten GLOF events that originated in Tibet AR (China) and crossed into Nepal (Table 2.1). For five, the triggering mechanism is unknown and the amount of damage incurred was also either slight or not known. Two events, in 1935 and 1964, were caused by collapse of the end moraines as a result of piping (seepage of water through the unconsolidated moraine material). Two, on 21 September 1964 and 27 August 1982 were triggered by glacier advance; one of these damaged a road and 12 trucks were destroyed. The GLOF event of 11 July 1981 was caused by an avalanche. It produced by far the most significant damage and is discussed in more detail below.

Sun Koshi, 11 July 1981 – Zhangzangbo Lake

On 11 July, 1981, the diversion weir at the Sun Koshi Hydroelectricity project, Nepal, was struck by a large flood and significant damage ensued. The flood also destroyed two bridges and extensive sections of the Arniko Highway. The total economic loss was in the order of US$ 3.0 million. At the time, the cause of the disaster was unknown. Only later, when a report by Xu Daoming (1985) was published, was it understood that the flood was the result of the drainage of the Zhangzangbo glacial lake north of the international border in Tibet AR (China). The triggering mechanism was described by Xu and Feng (1994) as an ice avalanche which produced a surge wave large enough to overtop the end moraine.

3 Defining Risk

Introduction

There has been a large amount of research over the last several decades on the dangers faced by people and property as a result of natural disasters: these disasters include events such as the recent (August 2010) flood in Pakistan, the March 2010 earthquake in Chile, the 2005 earthquake in Pakistan, and the giant tsunami triggered by an earthquake off the southwest coast of Sumatra in 2004. These disasters have presented scientists, engineers, and technicians with the serious challenges of developing predictive models and early warning systems.

There are also other events of smaller but still serious magnitude such as volcanic eruptions, floods, cyclones, avalanches, droughts, and heat waves. The threat perceived from the outburst of glacial lakes may be at least an order of magnitude lower in importance than these other types of catastrophe; nevertheless people and owners of property located in the path of potential GLOF events would hardly make that distinction. Thus, the purpose of this report is to develop an approach that can be used to reduce the risk of such events in the Nepal Himalayas; and that can also be used as a basis to help reduce the threat of such events throughout the greater Hindu Kush-Himalayan region.

Hazard and risk

For GLOF events, the risk needs to be defined in relation to the people and property located downstream. This is by no means easy because the phenomenon that leads to the risk is extremely difficult to predict. It is also important to note that 'at risk' modern developments such as hydroelectric facilities, tourist hotels and tea shops, bridges, and roads have increased in number over the last twenty or more years and will continue to do so. Thus the scale of the risk envisaged is increasing.

In general terms, **risk** is defined as a combination of the magnitude and frequency of the threatening event (the **hazard**) in relation to the **vulnerability** of the people and property that may be affected by the event. The Joint Technical Committee on Landslides and Engineered Slopes (JTC1) has defined risk as a 'measure of the probability and severity of an adverse effect to life, health, property, or the environment' (JTC1 2004). Thus, natural risks consist of two components: the hazard, i.e., the probability of a major natural event happening, and the vulnerability, i.e., the potential casualties and/or damage. In simple terms, Risk = Hazard x Vulnerability.

Hazard is the 'probability that a particular threat occurs within a given period of time' and includes the temporal distribution of the threat; the **vulnerability** is the 'degree of loss to a given element, or set of elements within the area affected by a hazard', or to a 'set of conditions and processes resulting from physical, social, economic, and environmental factors' (JTC1 2004). Further, **'threat'** is defined as a 'natural phenomenon that could lead to damage, described in terms of its geometry, mechanical, and other characteristics'. The threat can be an existing one (such as a creeping slope) or a potential one (such as a rockfall or GLOF); its spatial distribution (sometimes referred to as hazard disposition) is the **'susceptibility'**. Threat therefore describes the process and magnitude of a dangerous event (JTC1 2004).

Magnitude is usually approached by geophysical investigation: in the case of a GLOF event, it is the volume of water that is likely to be released under the defined worst-case scenario, its rate of release, and the extent to which it may destabilise slopes downstream.

Frequency is an important element in the equation. It is especially difficult to estimate frequency. The number of previous events, if large, will assist in statistical evaluation of the probability of such events in future. In the case of GLOFs, however, very few have ever occurred, either in Nepal or in the neighbouring mountains of Tibet AR (China), and repeat discharge from a single source is particularly rare. Often, once a moraine-dammed lake has burst, the process dismantles the end moraine to such an extent that the danger of a subsequent discharge is either minimised or eliminated.

Vulnerability is usually the simplest part of the equation. It can be determined in two steps:

1. Take a worst-case scenario of a lake outburst and determine the surface perimeter that would be affected below the source.
2. Compile the statistics for population and property located within the perimeter and calculate the dollar value, assuming total loss. Usually the value of personal property contained within households and indirect costs are not included. Nevertheless, these can be significant.

It is acknowledged, of course, that human life is invaluable. Calculations of loss in monetary terms, however, usually include an estimate of the property values (either actual or replacement value) and the number of lives.

Problems in investigating risk for GLOFs in Nepal

In the present report we estimate the probability as well as the magnitude of potential GLOF events. This task is fraught with imponderables since the probability of a lake outburst cannot be predicted with any reasonable level of certainty. This introduces another dimension of the problem, that of perception or what people who live downstream from a glacial lake think about the impending threat. This is a considerable problem because, over the past twenty years or so, exaggerated reporting in both the news media and the semi-scientific literature, and widespread reaction to it, have influenced this perception.

The widespread tendency to exaggerate, even to indulge in melodrama and falsification, requires a vigorous response. Nevertheless, GLOFs have occurred in the recent past, they have taken lives and destroyed property, and there is no doubt that such catastrophes will occur in the future, if not tomorrow. The difficulty lies in balancing all of these elements as well as estimating the costs of any mitigation efforts and/or early warning systems. When only limited resources are available, it is important to have a clear perspective of costs and benefits.

Criteria Used in Determining Hazard

In the absence of any definitive predictors of catastrophic drainage from a lake, it is necessary to ascertain which characteristics associated with lakes must be taken into account and evaluated in order to estimate the likely hazard.

In this report, glacial lakes are divided into two broad categories: lakes that form between the terminus of a steeply-sloped retreating glacier and its end moraine; and those that develop through growth and amalgamation of meltwater ponds on the lower, almost horizontal surface of a glacier tongue. Those in the first category are called 'clean-ice glacial lakes' because the associated steeply sloping glaciers generally have little surface debris; those in the second category are called 'supra-glacial' lakes. Supra-glacial lakes generally form on the surface of glaciers that are almost entirely covered by a thick mantle of debris and have low gradients, indicating that they are either moving very slowly or are totally stagnant, at least in their lower sections where the lakes form. As supra-glacial lakes enlarge and develop, the remnant glacier ice beneath them melts, and they slowly evolve into moraine-dammed lakes, thus they are often referred to as 'supra-glacial and/or end moraine-dammed lakes'.

The typical mechanisms of outburst differ between the two types of lake. For example, clean-ice glaciers with steep surface slopes are usually flanked by precipitous mountain walls that support hanging glaciers and snow and ice fields that periodically form avalanches. Ice, snow, and rock avalanches into these lakes can initiate surge waves causing the lake to overtop its moraine dam. In contrast, supra-glacial lakes are generally in contact with their glacier termini and contained within high and steep lateral moraines. The lateral moraines are usually separated from the precipitous mountain valley walls by sub-parallel dry valleys, which protect the lakes from ice- or snow-avalanches, rock falls, and landslides from the valley walls. Thus, they are only rarely subject to major release triggers that could induce surge waves and lead them to overtop their end moraine dams.

The largest of the existing glacial lakes in Nepal are those that began as a series of supra-glacial meltwater ponds. They include Tsho Rolpa, Imja Tsho, and Thulagi Lake, all of which began to form some 50 to 60 years ago. All three lakes are now more than two to three kilometres long with maximum depths close to 100 metres and storage capacities over $35x10^6$ m^3.

The critical element determining the stability of supra-glacial or end moraine-dammed lakes is the strength and cohesion of the end moraine. In this case the primary trigger is anything that compromises the integrity of the end moraine. A first consideration is the hydrostatic pressure on the dam caused by the volume of water in the lake and anything that can increase that volume. Any of a number of associated triggers that can compromise the stability of the moraine dam should be considered. These can include the degree of consolidation as resistance to seepage (piping) of lake water through the dam; sheer increase in hydrostatic pressure as the lake enlarges; the melting of ice cores and permafrost within the end moraine; and any downcutting of the outlet stream. The possibility of a surge wave cannot be excluded but is considered to be extremely rare because of the surrounding topographic configuration.

Either mechanism (surge wave and moraine dam collapse) can trigger a GLOF event in both of the two types of glacial lake, but the likelihood is different. Most frequently, outbursts from 'clean-ice glacier' lakes are triggered by surge waves caused by avalanches, while outbursts from 'supra-glacial' lakes are initiated by the collapse of the moraine dam. This does not exclude the possibility of either or both mechanisms affecting either type of lake or the same lake. Furthermore, the partial distinction between the two sub-sets would be meaningless in the event of a major earthquake which, though probable, is highly unpredictable.

Chhukung village downstream of Imja Tsho, 14 October 2010

4 Mapping of Glaciers and Glacial Lakes

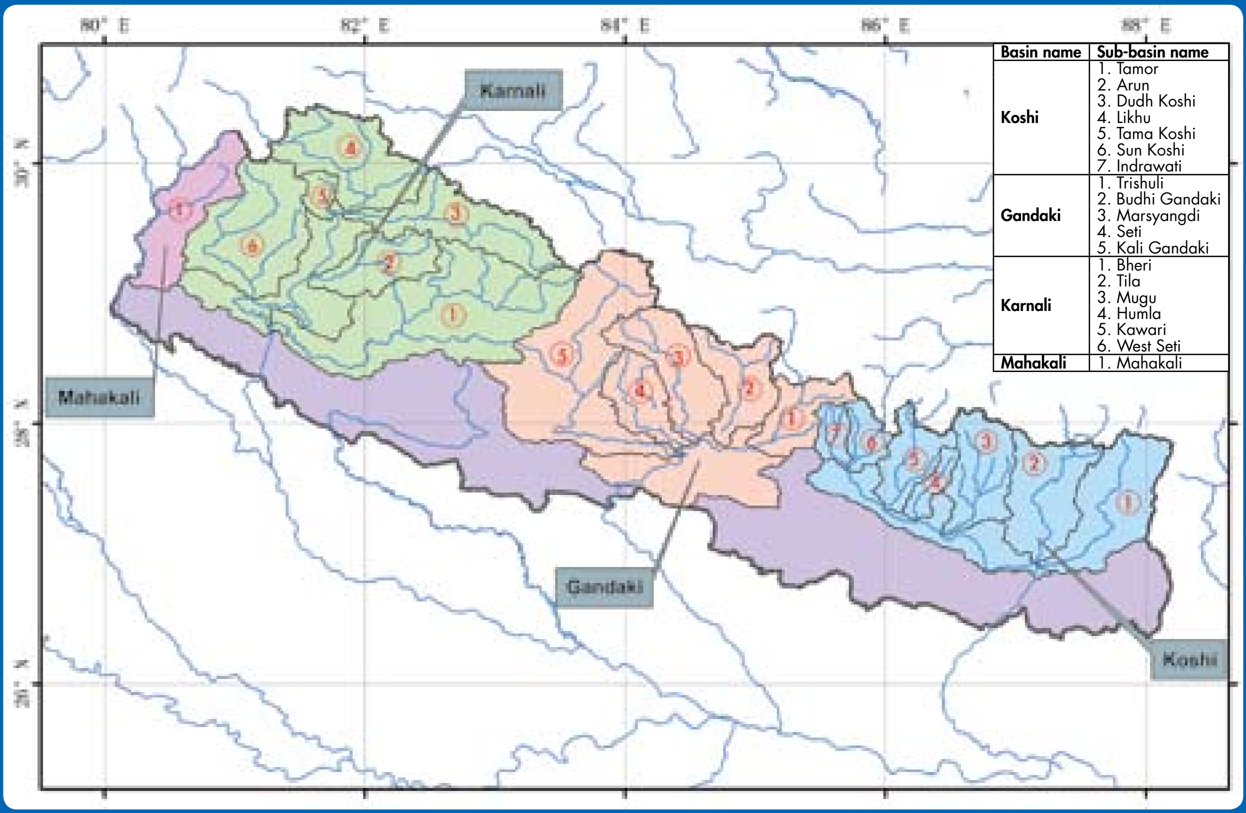
The Inventories for Nepal

An inventory of glaciers and glacial lakes in Nepal was prepared by ICIMOD in 1999/2000 with support from the United Nations Environment Programme, Regional Resources Centre for Asia and the Pacific (UNEP/RRC-AP). This inventory was based mainly on topographic maps published between 1960 and 1982; for areas where no maps were available, satellite images dating from 1999 and 2000 were used (Mool et al. 2001a).

In 2009/10, ICIMOD produced a new inventory for Nepal based on Landsat images taken in 2005 and 2006. A comparison between this new inventory and that of 2001 showed changes in many of the glacial lakes, which led to realisation of the need to reappraise these lakes in order to prioritise them for more detailed study. However, in making comparisons between different sets of data, it is important that the types of imagery used and the dates of their acquisition be as similar as possible; the earlier inventory was based on the only sources available at the time, but was far from optimum in this respect.

In both inventories, glaciers and glacial lakes were mapped and numbered according to river basins and sub-basins. For this, the Nepal Himalayas were divided into four major river basins from east to west: the Koshi basin; the Gandaki basin; the Karnali basin; and the Mahakali basin. Each was divided further into sub-basins (Figure 4.1).

Figure 4.1: **Major river basins and sub-basins in the Nepal Himalayas**



The Koshi river basin lies in eastern Nepal between latitudes 26°21′ and 28°13′ N, and longitudes 85°20′ and 88°13′ E. It has seven major sub-basins: Indrawati, Sun Koshi, Tama Koshi, Likhu, Dudh Koshi, Arun, and Tamor. The Arun, Tama Koshi, and Bhote Koshi-Sun Koshi rivers originate in TAR China, and flow south through the Nepal Himalayas. All other tributaries originate within the territory of Nepal and also flow southwards. The Sun Koshi river generally flows from northwest to southeast (Figure 4.1).

The Gandaki river basin lies in central Nepal between latitudes 27°46′ and 28°12′ N, and longitudes 82°44′ and 85°48′ E. It has five major sub-basins: Kali Gandaki, Seti, Marsyangdi, Budhi Gandaki and Trishuli.

The Karnali river basin lies in western Nepal between latitudes 29°04′ and 30°27′ N, and longitudes 80°33′ and 83°41′ E. It has six sub-basins: West Seti, Kawari, Humla, Mugu, Tila, and Bheri. Its river network includes the Bheri, Mugu Karnali, Humla Karnali, Kawari, Tila, and West Seti rivers. Generally, the rivers flow from north to south. The Humla Karnali river originates in TAR China.

The Mahakali river lies in the far west of Nepal; it flows towards the southwest and forms Nepal's western border with India. It has two main tributaries in Nepalese territory: the Chamelia river and the Surnagad river. The part of the Mahakali river basin lying in Nepal falls between latitudes 29°07′ and 30°04′ N, and longitudes 80°08′ and 81°07′ E and covers about one-third of the total area of the basin.

Mapping Glaciers

The methodology used for mapping Nepal's glaciers follows the recommendations developed for the World Glacier Inventory (WGI) by Müller et al. (1977) at the Temporary Technical Secretariat (TTS), Swiss Federal Institute of Technology (ETH), Zurich.

The attributes of glaciers used in mapping are as follows:

1. Unique identifier (basin and sub-basin name, glacier name, latitude, longitude, and highest, lowest, and mean elevations)
2. Physical parameters (area, length, and orientation of glacier)
3. Glacier type (class)
4. Source of database and date

ICIMOD's first glacier inventory covered a wide temporal range due to the limited data sources available at the time. This placed restrictions on its value for detailed analysis.

Ideally, glacier information should be compiled from a single source over a narrow temporal range. This opportunity was offered more closely when images became available from Landsat 5, 7 and Enhanced Thematic Mapper (TM/ETM+), since these have a narrower temporal base (2005±3 years). These images were used to prepare a new inventory, which therefore provides a more accurate base for analysis. Furthermore, the new mapping process was undertaken by applying a semi-automated approach using the 'eCognition' (Definiens Development-object base) and 'ERDAS Imagine' (pixel base) remote-sensing software to delineate glacier boundaries. Post-processing database management was carried out using ArcGIS software. The parameters selected were based on the 'Guidelines for the compilation of glacier inventory data from digital sources', which were reviewed by several members of the working and user groups of both the ESA GlobeGlacier and Global Land Ice Measurements from Space (GLIMS) communities (Bajracharya et al. 2009). The glacier inventory for Nepal is part of a larger inventory which is being prepared for publication.

The 2001 inventory identified 3,252 glaciers in Nepal covering an area of 5,324 sq.km (Mool et al. 2001a). The new inventory prepared using the Landsat 5 and 7 images mapped 3,808 glaciers with a total area of 4,212 sq.km (Table 4.1) (Bajracharya et al. 2010, Bajracharya and Maharjan 2010).

Table 4.1: **Distribution of glaciers in the river basins of Nepal**
(after Mool et al. 2001a, Bajracharya et al. 2010, Bajracharya and Maharjan 2010)

	2001 glacier inventory			2010 glacier inventory			
Basin	No. of glaciers	Total area (sq.km)	Mean area (sq.km)	No. of glaciers	Total area (sq.km)	Highest elevation (masl)	Lowest elevation (masl)
Koshi	779	1,410	1.81	843	1,180	8,437	3,962
Gandaki	1,025	2,030	1.98	1,337	1,800	8,093	3,273
Karnali	1,361	1,741	1.27	1,461	1,120	7,515	3,631
Mahakali	87	143	1.65	167	112	6,850	3,695
Total	**3,252**	**5,324**	**1.64**	**3,808**	**4,212**		

Mapping Glacial Lakes

For the inventory, glacial lakes were defined as all lakes in a river basin that lie above 3,500 m, are greater than 1000 sq.m in area, and are fed by glacial melt. The altitude was selected as representing the approximate lower limit of glacial moraine accumulations in Nepal. Glacial lakes may also exist beneath or within glaciers, but these are not usually visible on aerial images and so cannot be mapped. Thus such lakes were not included.

Classification of lakes

The glacial lakes were classified broadly into moraine-dammed, ice-dammed, erosion, and other lakes. The detailed classification is summarised in Table 4.2. Some of the more common types of lake in Nepal are described in the following.

Moraine-dammed lakes

As a glacier tongue thins and retreats, meltwater can become trapped in the trough between the glacier terminus and its end moraine. Lakes may also accumulate along the glacier margins, between the lateral moraine and the valley side. Depending on the topography of the glacial foreland inside the end moraine, small lakes may also accumulate in the numerous depressions that are characteristic of the terrain.

Supra-glacial lakes

The only ice-dammed lakes identified in Nepal are supra-glacial lakes. The recent period of atmospheric warming has caused many of the glaciers in the Nepal Himalayas to thin. The lower tongues of a large number of these glaciers are almost completely mantled with morainic debris and rock fall from the surrounding valley walls. In the early stages of down-melting, small ponds accumulate within the surface moraine. These ponds are inherently unstable and may drain englacially or through a lateral moraine before reaching significant dimensions. In many cases, however, they have grown in size as glacier melt continued, and have amalgamated into progressively larger supra-glacial lakes. While most of these lakes originate as small ponds, their progressive expansion has produced some of the largest of the Himalayan lakes. As lake expansion and glacial retreat continue, these supra-glacial lakes may merge with end-moraine dammed lakes. Because of the enormous volume of such lakes, they are often perceived to be among the most critical.

Erosion lakes

Glacial erosion lakes are bodies of water that form following glacial erosion and ‘over-deepening’. They exist in a variety of forms such as in depressions formed by cirque glaciers and as glacial valley lakes that accumulated in depressions after the eroding glacier retreated or disappeared. They may be partially dammed by very old end moraines. They have usually been in existence for hundreds or even thousands of years.

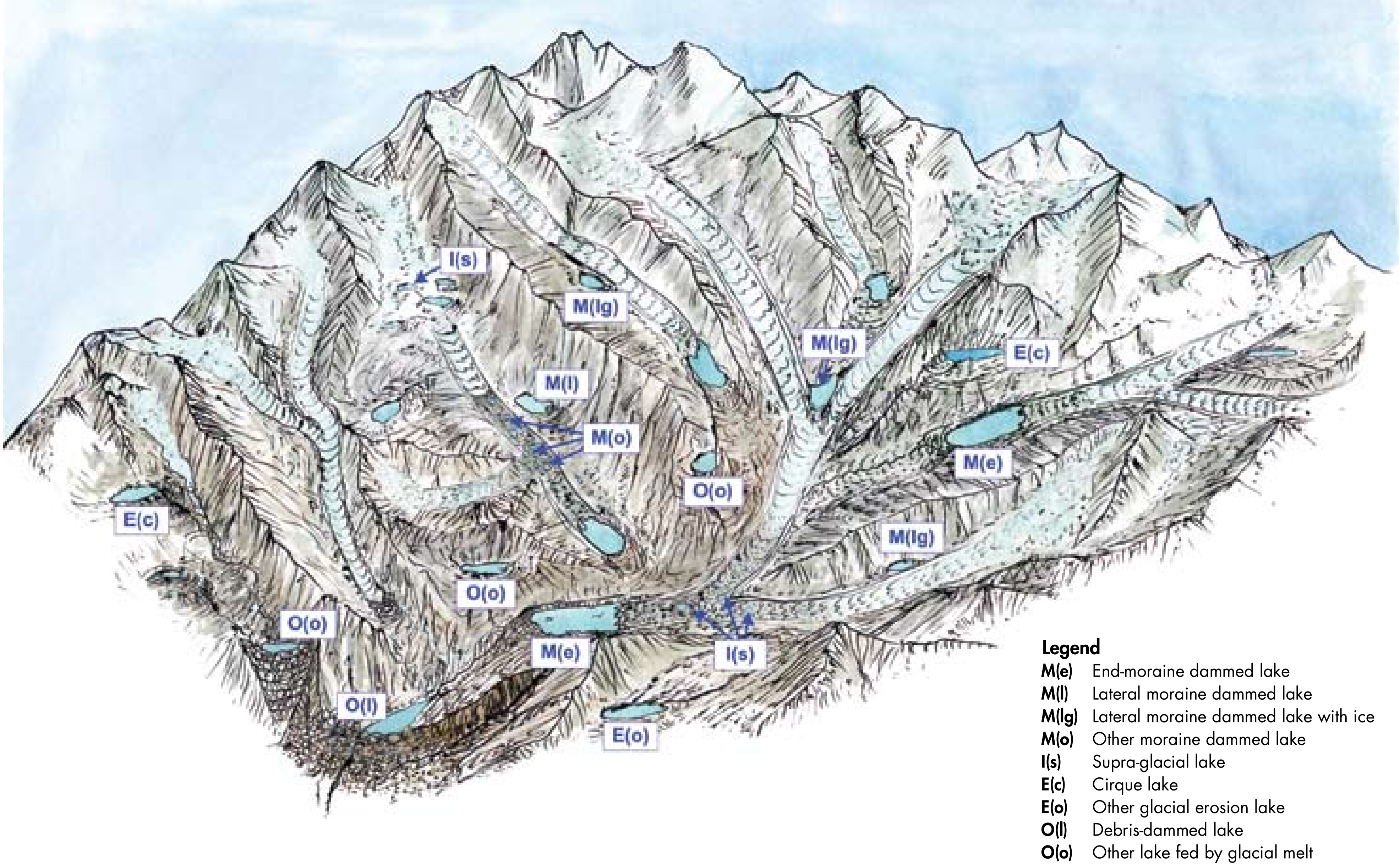
Other glacial lakes

Rock falls, debris flows, and landslides often send masses of rock and soil debris on to valley floors damming local streams originating in glaciers. Bodies of water may also form amongst the uneven hummocks created by these deposits.

Table 4.2: **Classification of glacial lakes: a. table** (below) **and b. schematic diagram** (opposite page)

Glacial lake type	Code	Definition	Notes
Moraine-dammed lake	**M**	Lake dammed by moraine following glacial retreat	
End-moraine dammed lake	M(e)	Lake dammed by end (terminal) moraines	Usually touches the walls of the side moraines, but the water is held back by the end moraine (dam), lake usually, but not necessarily, in contact with the glacier, and may have glacier ice at the lake bottom (defined in some other classifications as 'advanced form of supraglacial').
Lateral moraine dammed lake (ice free)	M(l)	Lake dammed by lateral moraine(s) not in contact with glacial ice	Lake is held back by the outside wall of a lateral moraine, i.e., away from the former glacial path; lake may be in the fork formed between two lateral moraines of a main glacier and a glacier in a tributary valley; 'ice free' means the lateral moraine itself is no longer in contact with the glacier.
Lateral moraine dammed lake (with ice)	M(lg)	Lake dammed by lateral moraine(s) in contact with glacial ice	As above, but the lateral moraine is in contact with the glacier ice.
Other moraine dammed lake	M(o)	Lake dammed by other moraines (includes kettle lakes and thermokarst lakes)	
Ice-dammed lake	**I**	Lakes dammed by glacier ice	.
Supra-glacial lake	I(s)	Pond or lake on the surface of a glacier	Most common type of ice-dammed lake in the Nepal Himalayas
Glacier ice-dammed lake	I(d)	Lake dammed by glacier ice with no lateral moraines	Dammed by the glacier ice, with no lateral moraine; can be at the side of a glacier between the glacier margin and valley wall Found elsewhere in the Hindu Kush-Himalayan region, but not in Nepal Himalayas
Glacier erosion lake	**E**	Bodies of water that form as a result of an earlier glacial erosion process, which accumulate in depressions after the glacier has retreated or melted away	
Cirque lake	E(c)	A small pond occupying a cirque	
Glacier trough valley lake	E(v)	Lakes formed in the glacier trough as a result of the glacier erosion process	For example ribbon lakes
Other glacier erosion lake	E(o)	Bodies of water occupying depressions formed by the glacial erosion process; these are usually located on the mid-slope of hills, but not necessarily in a cirque.	
Other glacial lakes	**O**	Lakes formed in a glaciated valley, and fed by glacial melt, but damming material not directly part of the glacial process	
	O(l)	Debris-dammed lake	Lake formed by dam following a debris fall, rock avalanche, or landslide in a glacial valley and fed by glacial melt
	O(a)	Artificial lake	Lake formed by a man-made dam in a glacial valley and fed by glacial melt
	O(o)	Other lakes fed by glacial melt	

Table 4.2: **Classification of glacial lakes: b. schematic diagram**



Legend

M(e)	End-moraine dammed lake
M(l)	Lateral moraine dammed lake
M(lg)	Lateral moraine dammed lake with ice
M(o)	Other moraine dammed lake
I(s)	Supra-glacial lake
E(c)	Cirque lake
E(o)	Other glacial erosion lake
O(l)	Debris-dammed lake
O(o)	Other lake fed by glacial melt

Materials and Tools

Landsat satellite images (World Geodetic System 1984, i.e., 'WGS 84' projection) from 2005/06 were used as the basic source of data for developing the present mapping and inventory work. These images can be downloaded freely from the United States Geological Survey (USGS) and Global Land Cover Facility (GLCF). Satellite images from 2000 and 2001 had to be used for a small area of the Mahakali basin because there were no cloud- and snow-free images available for any date after 2001.

Information on the elevation of the glacial lakes was derived from the Shuttle Radar Transmission Mission Digital Elevation Model (SRTM DEM) and Advanced Space-borne Thermal Emission and Reflection Radiometer (ASTER) Global DEM. This data source was used to detect the boundaries of glacial lakes and to help classify them. Google Earth satellite images were used to verify the glacial lake inventory data. A combination of open source remote sensing and GIS software packages, such as Google Earth, Quantum GIS, Integrated Land and Water Information System (ILWIS), Postgre/ PostGIS, and Python, were used to edit, manage, and analyse the data.

Both information on lakes, and supporting information related to possible impact on the downstream areas, can also be obtained using high resolution images like IKONOS, QuickBird, or OrbView as shown by other authors (Kääb et al. 2005).

Detection of glacial lakes

Detection of glacial lakes using multispectral imagery involves discriminating between water and other types of surface. Delineation of surface water can be achieved using spectral reflectance differences. Water strongly absorbs light in the near- and middle-infrared wavelengths (0.8 – 2.5 μm). The Normalised Difference Water Index (NDWI) was used for automated glacial lake detection (Huggel 2002) followed by visual interpretation. DEM and Google Earth were used for better visualisation, especially for lakes in shadow and/or snow-covered areas.

Parameters of the glacial lake inventory

Altogether 18 different parameters were considered in the glacial lake inventory, divided into four groups: information about the hydrological basin, data about the glacial lake, data sources, and information about the associated glacier:

- Information about the hydrological basin
  - Name of basin
  - Name of sub-basin
  - Drainage
- Source of database and date
  - Source of elevation data
  - Data source
  - Data source date
- Information about the associated glacier
  - Code
  - Glacier name
  - Distance from lake
- Data about the glacial lake
  - Code
  - Longitude
  - Latitude
  - Elevation
  - Lake area
  - Lake length
  - Orientation
  - Class
  - Level of potential hazard

Distribution and characteristics of glacial lakes

The inventory identified a total of 1,466 glacial lakes in Nepal (Figure 4.2 and Table 4.3). Nine lakes were mapped in the Nepalese part of the Mahakali river basin with a total area of 0.137 sq.km; 742 lakes were mapped in the Karnali basin with a total area of 29.147 sq.km — the largest number and greatest lake area in any one basin; 116 glacial lakes were mapped in the Gandaki basin with a total area of 9.538 sq.km — the largest average size in any basin (0.082 sq.km); and 599 lakes were mapped in the Koshi basin with a total area of 25.958 sq.km.

Figure 4.2: **Location of glaciers and glacial lakes in Nepal**

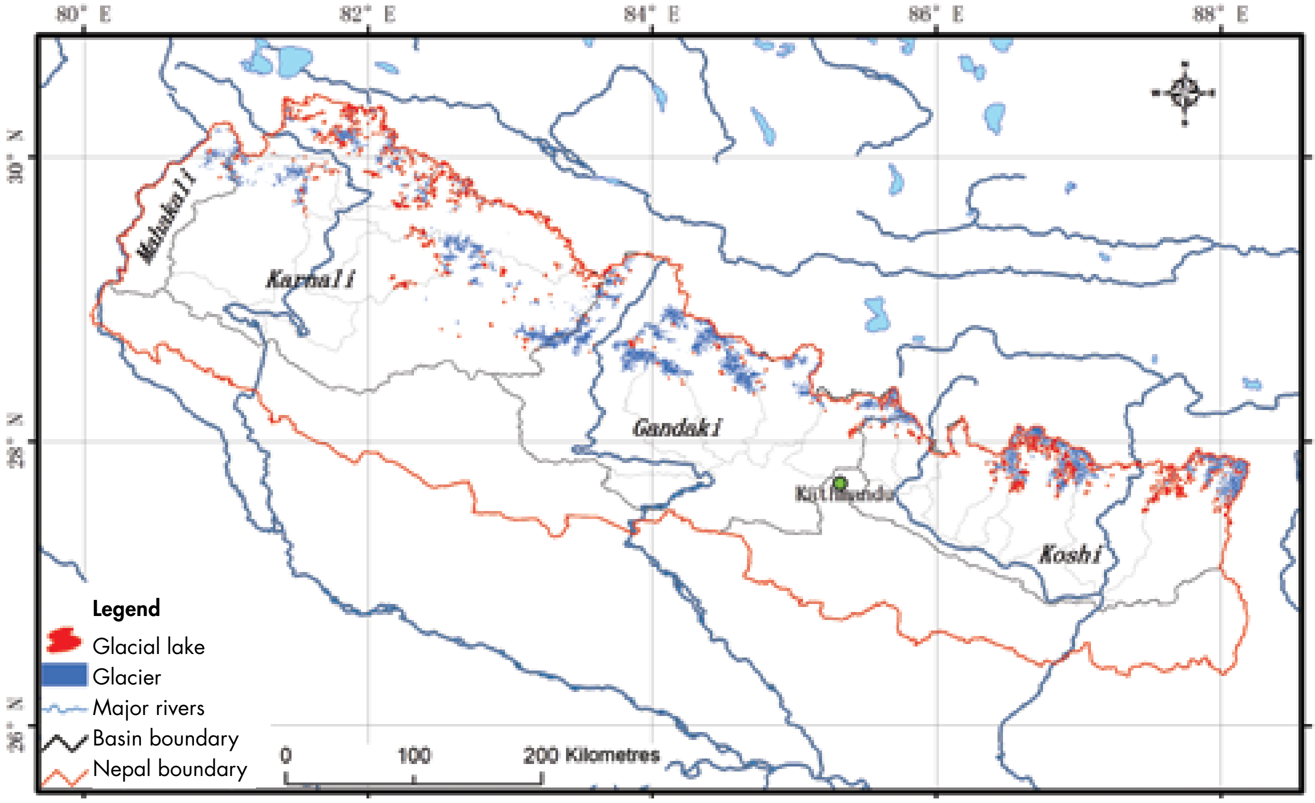
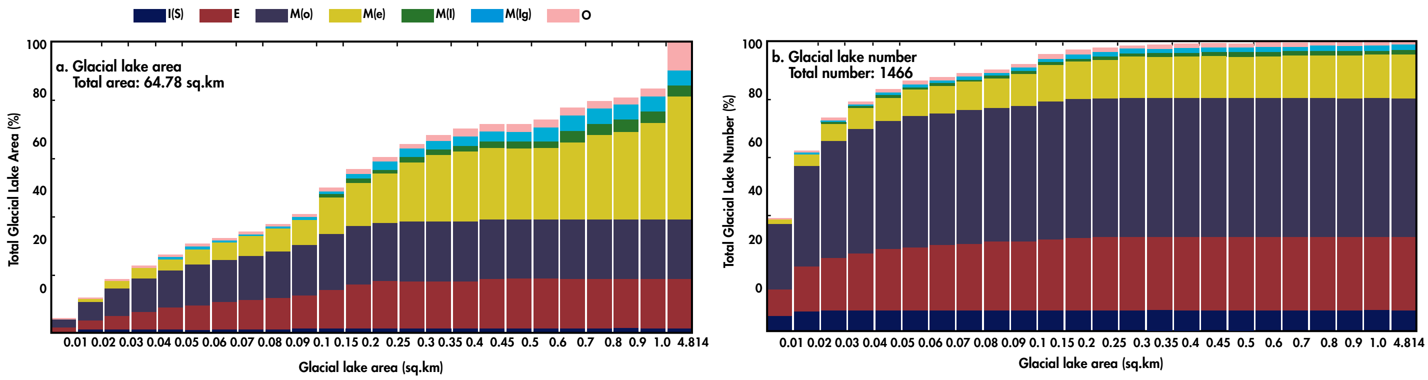


Table 4.3: **Glacial lakes and their area in the river basins and sub-basins of Nepal**

Basin	Sub-basin	Glacial lakes				Mean area (sq.km)	Max area (sq.km)	Min area (sq.km)
		Number	% of total	Area (sq.km)	% of total			
Koshi	Tamor	209	14.26	6.584	10.16	0.032	0.615	0.001
	Arun	81	5.53	3.284	5.07	0.041	1.122	0.002
	Dudh Koshi	243	16.58	13.207	20.39	0.054	0.943	0.002
	Likhu	13	0.89	0.312	0.48	0.024	0.082	0.003
	Tama Koshi	24	1.64	2.156	3.33	0.090	1.452	0.003
	Sun Koshi	17	1.16	0.306	0.47	0.018	0.061	0.004
	Indrawati	12	0.82	0.109	0.17	0.009	0.024	0.003
	Basin total	**599**	**40.86**	**25.958**	**40.07**	**0.043**	**1.452**	**0.001**
Gandaki	Trishuli	50	3.41	1.678	2.59	0.034	0.181	0.003
	Budhi Gandaki	12	0.82	0.709	1.09	0.059	0.250	0.002
	Marsyangdi	22	1.50	5.158	7.96	0.234	3.322	0.003
	Seti	6	0.41	0.113	0.17	0.019	0.033	0.013
	Kali Gandaki	26	1.77	1.880	2.90	0.072	0.670	0.003
	Basin total	**116**	**7.91**	**9.538**	**14.72**	**0.082**	**3.322**	**0.002**
Karnali	Bheri	56	3.82	6.936	10.70	0.124	4.814	0.002
	Tila	73	4.98	3.576	5.52	0.049	0.434	0.003
	Mugu	218	14.87	5.020	7.75	0.023	0.382	0.002
	Humla	346	23.60	12.189	18.82	0.035	0.619	0.001
	Kawari	24	1.64	0.774	1.19	0.032	0.160	0.003
	West Seti	25	1.71	0.652	1.00	0.026	0.298	0.002
	Basin total	**742**	**50.61**	**29.147**	**45.00**	**0.039**	**4.814**	**0.001**
Mahakali	Mahakali	9	0.61	0.137	0.21	0.015	0.049	0.003
	Basin total	**9**	**0.61**	**0.137**	**0.21**	**0.015**	**0.049**	**0.003**
	Total	**1466**	**100**	**64.780**	**100**	**0.044**	**4.814**	**0.001**

Figure 4.3 and Table 4.4 show the cumulative distribution of glacial lakes according to their type, number, and area. The majority of lakes are moraine-dammed (975 lakes occupying 72% of the total lake area); supra-glacial lakes, mostly small with an average size of 0.009 sq.km, represent only 1.5 % of the total glacial lake area; erosion lakes represent 17% of the total lake area; and other glacial lakes 9.5%.

Figure 4.3: **Cumulative distribution of glacial lakes** (a: area % and b: number %)



I(s) = supra lake, E = erosion lake, M(o) = other moraine, M(e) = end moraine, M(l) = lateral moraine, M(lg) = lateral moraine with glacier, O = other glacial lake

Table 4.4: **Summary of number and area of different types of glacial lakes in Nepal**

Main type	Sub type	Total number		Total area		Mean area (sq.km)	Max area (sq.km)	Min area (sq.km)
		Number	%	Area	%			
Moraine dammed lake	End-moraine dammed lake	227	15.5	27.526	42.5	0.122	3.322	0.003
	Lake dammed by lateral moraine not in contact with glacial ice	15	1.0	2.358	3.6	0.157	0.670	0.001
	Lake dammed by lateral moraine in contact with glacial ice	33	2.3	3.611	5.6	0.109	0.570	0.004
	Other moraine- dammed lake	700	47.8	13.269	20.5	0.019	0.271	0.001
	Total	**975**	**66.6**	**46.764**	**72.2**	**0.407**	**4.833**	**0.009**
Ice dammed lake	Supra-glacial lake	107	7.3	0.985	1.5	0.009	0.100	0.002
Glacier erosion lake	Cirque lake	121	8.3	6.915	10.7	0.057	0.434	0.003
	Trough valley lake	5	0.3	0.500	0.8	0.100	0.235	0.014
	Other glacial erosion lake	242	16.5	3.450	5.3	0.014	0.168	0.001
	Total	**368**	**25.1**	**10.865**	**16.8**	**0.171**	**0.837**	**0.018**
Other glacial lake		16	1.1	6.166	9.5	0.385	4.814	0.011
	Total	**1,466**	**100**	**64.780**	**100**			

Forty-nine of the mapped lakes were larger than 0.2 sq.km; together they occupy 28.45 sq.km or 43.9% of the total glacial lake area of Nepal. The average size of the lakes overall was 0.044 sq.km. Thus the great majority of lakes are small and may not draw significant attention in terms of potential hazards. However, small lakes can also lead to disasters when they are included in chain reactions and process combinations, or where there is high downstream vulnerability. Equally, small lakes that do not have a significant hazard potential at present may enlarge over a short period and become a potential hazard source.

A repeat inventory is considered a necessary precaution, and close monitoring of small lakes should not be ignored (Narama et al. 2008). The current study focused on larger lakes because of their large erosive power to longer distances downstream where infrastructure is located, whereas small scale events generally have more localised impacts with their limits at headwaters where there is generally less infrastructure or large scale economic activity.

Figure 4.4 shows the distribution of glacial lakes in relation to area, elevation, and longitude. In general, the larger valley glaciers with termini extending below 5,000 metres above sea level (masl) have well-developed glacial lakes. The majority of lakes are located at elevations of between 4,500 and 5,000 masl. The larger, moraine-dammed lakes are mostly concentrated in the eastern parts of the country.

Figure 4.5 shows the spatial distribution of lakes by type and sub-basin: the size of the circles represents the cumulative area of lakes of each type in three different size ranges. Thus the figure shows that the Tamor sub-basin has more glacier erosion lakes (117) of large size with a total area of 2.948 sq.km (Figure 4.5g); whereas large lakes dammed by end moraines are most numerous (53 lakes) in the Dudh Koshi sub-basin where they occupy a total area of 7.842 sq.km (Figure 4.5b). Other moraine dammed types of lake are concentrated in the Humla sub-basin (248 lakes), where they cover a total area of 4.601 sq.km (Figure 4.5e). Other glacial lakes of large size are concentrated in the Bheri sub-basin (2 lakes), where they cover a total area of 4.844 sq.km (Figure 4.5h).

Figure 4.4: **Distribution of glacial lakes in relation to longitude and elevation; the line graph shows the distribution of lake area**

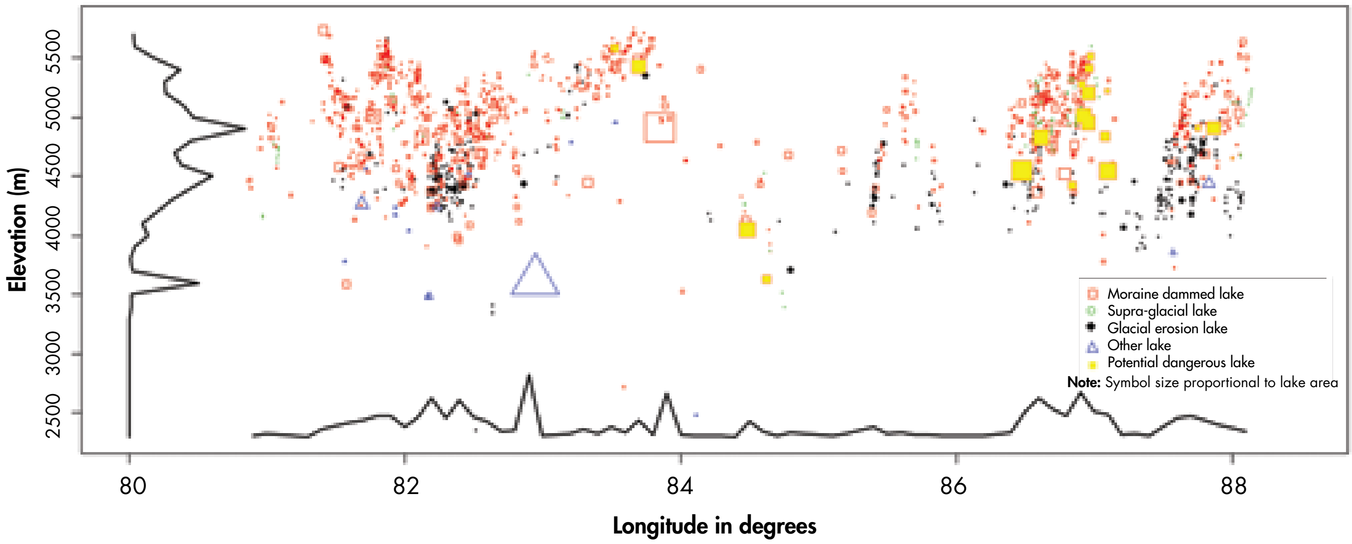
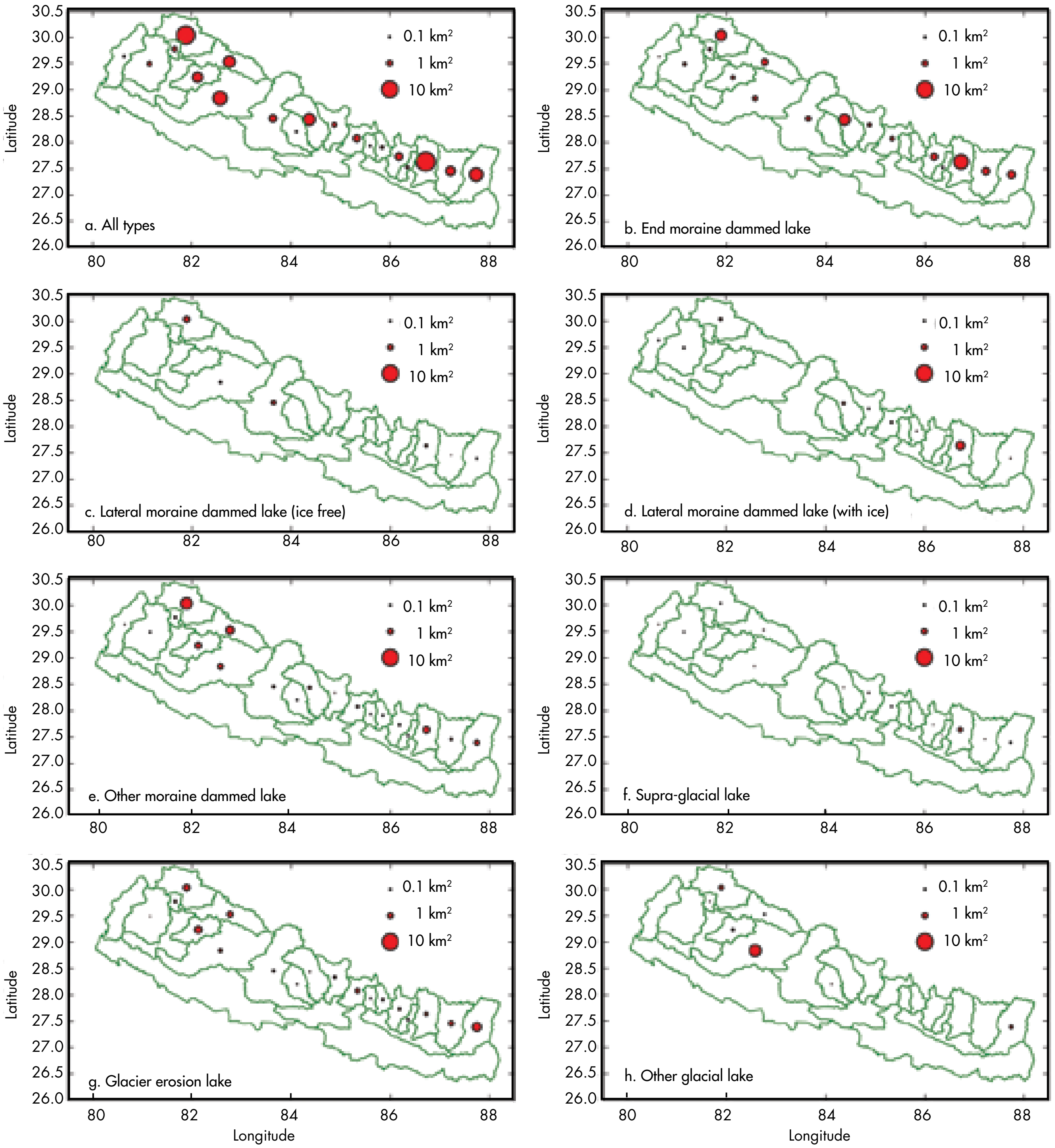


Figure 4.5: **Graphical representation of cumulative area of lake types in each sub-basin, (the size of the circle indicates cumulative area)**



Names of individual sub-basins are given in Figure 4.1

Changes Over Time

The inconsistency between the data sources in the inventory of 2001 and the present study presents a problem in obtaining a meaningful comparison as the two inventories are not strictly equivalent. Nevertheless, an attempt was made to identify the main differences (Table 4.5). The total number of lakes decreased from 2,323 to 1,466, a reduction of 37%. The total area also decreased from 75.6 to 64.8 sq.km, or 14%, whereas the average lake area increased from 0.033 sq.km to 0.044 sq.km, or 33%. The differences are to some extent the result of the use of different sources of data and different methodologies. Nonetheless, some of the changes identified do appear to be the result of very small supra-glacial lakes (2001) coalescing to form fewer but larger lakes. At the same time, some smaller lakes identified in the 2001 study have now totally disappeared. The changes indicate that the situation may be evolving rapidly. It confirms the need for periodically repeated surveys (for example every 5 to 10 years) using strictly comparable data sources.

Table 4.5: **Comparison of number and area of glacial lakes between the 2001 and 2009[*] inventories**
(after Ives et al. 2010)

Basin/ Sub-basin	Lakes in 2001 inventory		Lakes in 2009 inventory		Comparison 2009/2001	
	Number	Area (sq.km)	Number	Area (sq.km)	Number (%)	Area (%)
Koshi River Basin						
Tamor	356	7.32	209	6.57	-41.29	-10.22
Arun	109	2.53	81	3.28	-25.69	29.53
Dudh Koshi	473	13.1	243	13. 19	-48.63	0.89
Likhu	14	0.22	13	0.31	-7.14	40.78
Tama Koshi	57	1.26	24	2.15	-57.89	71.07
Sun Koshi	35	0.41	17	0.31	-51.43	-25.73
Indrawati	18	0.28	12	0.11	-33.33	-60.79
Basin sub-total	**1062**	**25.1**	**599**	**25.92**	**-43.60**	**3.30**
Gandaki River Basin						
Trishuli	117	2.03	50	1.68	-57.26	-17.44
Budhi Gandaki	37	0.64	12	0.71	-67.57	10.78
Marsyangdi	78	6.28	22	5.16	-71.79	-17.90
Seti	10	0.26	6	0.11	-40.00	-56.54
Kali Gandaki	96	3.29	26	1.88	-72.92	-42.86
Basin sub-total	**338**	**12.50**	**116**	**9.53**	**-65.68**	**-23.73**
Karnali River Basin						
Bheri	152	9.16	56	6.94	-63.16	-24.26
Tila	71	4.97	73	3.58	2.82	-28.01
Mugu Karnali	280	8.56	218	5.03	-22.14	-41.29
Humla Karnali	345	13.01	346	12.19	0.29	-6.29
Kawari	44	1.57	24	0.77	-45.45	-50.70
West Seti	15	0.40	25	0.65	66.67	63.00
Basin sub-total	**907**	**37.67**	**742**	**29.16**	**-18.19**	**-22.59**
Mahakali Basin						
Mahakali	16	0.38	9	0.137	-43.75	-63.95
Total	**2,323**	**75.64**	**1,466**	**64.75**	**-36.89**	**-14.36**

Note: data for the 2001 survey were derived from topographic maps based on survey data from the 1950s and 60s and satellite images of between 1984 and 1994; data for the 2009 survey were derived from satellite images from 2005/06 (see text).

Dudh Koshi and Imja river valley from Pheriche, 14 October 2010

5 Prioritisation of Critical Lakes

Identification of Critical ('Potentially Dangerous') Lakes

Application of remote sensing has become a fundamental requirement for any assessment of the potential hazard posed by the rapid formation of new glacial lakes and the continued enlargement of existing ones. However, remote-sensing techniques are limited in their ability to see below the surface; and ground-based geophysical surveys such as bathymetric and borehole surveys are needed in order to investigate below the surface. Given the geographic extent and unusually challenging accessibility of the Nepal Himalayas, and the large number of lakes involved, it is clear that only a very small percentage of lakes will ever be visited in the field. It would also be impossible to carry out detailed field investigations of all lakes identified as critical because such investigations are difficult, time consuming, and expensive. Emphasis must be placed on the relatively small number of lakes that can be identified as especially vulnerable to sudden outbreak (Ives et al. 2010). This is not only because of the degree of danger to which people and infrastructure may be exposed, but also to ensure the most efficient use of limited available resources (WECS 1987).

In order to select lakes for detailed field study, they must be ranked in order of their apparent level of instability. This process has two aspects: (1) evaluation of the current degree of lake instability from a purely geophysical point of view; and (2) determination of the potential for downstream damage and loss of life in the event of actual lake outburst. The two foci must be examined separately and then combined (Ives et al. 2010).

Various researchers have applied remote sensing methods using space borne imagery and in situ field surveys for the assessment of glaciers and glacial lake hazards in high mountain areas (Yamada 1998a, 1998b; Reynolds 1999; Mool et al. 2001a, 2001b; Huggel et al. 2002; Bolch et al. 2008; Fujita et al. 2009; Watanabe et al. 2009). Statistical and remote sensing-based approaches have been used to investigate the probability of catastrophic drainage of moraine-dammed lakes in southwestern British Columbia, Canada (McKillop and Clague 2007). Glacial lake hazard assessment has been undertaken in the Swiss Alps using three scale levels of remote sensing with a progressive focus on critical glacial lakes (Huggel et al. 2002). In very remote regions, such as the Cordillera Carabaya in the Peruvian Andes, remote sensing has proven to be of great value, being virtually the only tool available to fill gaps in information (Huggel et al. 2003).

Huggel et al. (2004) presented the procedures for first order assessment of GLOF and other glacial hazards such as ice avalanches and debris flows. The assessment procedure must consider basic glaciological, geomorphological, and hydraulic principles together with experience gained from previous events. However, it is difficult to estimate the probability of occurrence of such hazards because of the rapid changes in the nature of glacial systems (Huggel et al. 2004).

In the current study, an attempt was made to approach the large number of lakes using a multi-scale or multi-level process starting from the regional scale (preliminary reconnaissance) and proceeding to the local scale (detailed information gathering) (Mool et al. 2001a; Huggel et al. 2002), with a selection of the most critical lakes at each level. First, very small lakes were excluded. The remaining lakes were then further evaluated using a range of geomorphological and physical criteria to identify those warranting further investigation. The selected lakes were studied in more detail using a list of criteria to further reduce the total. Those remaining were ranked on the basis of physical and socioeconomic parameters. This resulted in a final list that was further divided into three groups: high priority lakes that required detailed field investigation and mapping; medium priority lakes to be closely monitored and reconnoitred in the field; and low priority lakes designated for periodic observation.

Selection Process

Primary selection

The current mapping of glacial lakes in Nepal includes all those with an area greater than 0.001 sq.km. Those with an area above 0.02 sq.km (559 in total) were considered large enough to cause damage downstream if they burst out; this potential would be heightened if they are associated with a glacier. A total of 49 lakes were identified in this manner. These were further evaluated as discussed below.

Selection of critical lakes warranting further investigation

Evaluation of the possibility of catastrophic drainage is based on the characteristics of a lake, its dam, associated glaciers, and other topographic features (Mool et al. 2001a). The factors taken into account include the size; rate at which the lake is expanding; position with respect to the associated glacier; height of the moraine dam; overtopping height (free board); origin of the lake (supra, cirque, moraine dammed); physical condition of the surroundings, such as the existence of hanging glaciers or potential rock and debris fall or slides; and the volume of water that could drain out.

The following criteria were identified in the step-wise approach adopted by ICIMOD for the initial inventory study to identify critical lakes warranting further investigation ('potentially dangerous') in Bhutan, TAR/China, India, Nepal, and Pakistan (Mool et al. 2001a; Mool et al. 2001b; Mool and Bajracharya 2003; Bhagat et al. 2004; Sah et al. 2005; Roohi et al. 2005; Wu Lizong et al. 2005):

1. Large size and rapid expansion
2. Increase in water level
3. Intermittent activity of supra-glacial lakes
4. Position in relation to moraines and associated glacier
5. Dam condition
    i. Narrow crest area
    ii. No drainage outflow or outlet not well defined
    iii. Steepness of slope of the moraine walls
    iv. Existence and stability of ice core and/or permafrost within moraine
    v. Height of moraine
    vi. Mass movement, or potential mass movement, on the inner slope and/or outer slope of moraine
    vii. Breached and closed in the past and the lake refilled with water
    viii. Seepage through the moraine walls
6. Glacier characteristics
    i. Condition of associated glacier
    ii. Hanging glacier in contact with or very close to lake
    iii. Large glacier area
    iv. Rapid glacier retreat
    v. Debris cover on the lower glacier tongue
    vi. Gradient of glacier tongue
    vii. Presence of crevasses and ponds on glacier surface
    viii. Toppling or collapsing of ice from the glacier front
    xi. Icebergs breaking off glacier terminus and floating into lake
7. Physical conditions of surroundings
    i. Potential rock fall and/or slide (mass movement) sites around the lake
    ii. Large snow avalanche sites immediately above
    iii. Neo-tectonic and earthquake activity
    iv. Climatic conditions, especially large inter-annual variations
    v. Very recent moraines of tributary glaciers that were previously part of a former glacier complex, and with multiple lakes that have developed due to retreat of several glaciers in close proximity (e.g. Lunana area in Pho Chu basin, Bhutan)
    vi. Sudden advance of a glacier towards a lower tributary or main glacier which has a well-developed frontal lake

The same criteria were used in the present study. They were evaluated for individual lakes based on existing field observations (where available), processes and records of past events, geomorphological and geotechnical characteristics of the lake and surroundings, and other physical conditions. Many of the criteria were derived from remote sensed data. Geomorphic features and processes are very distinctive in the high spatial resolution satellite images and aerial photographs, and physical parameters of glaciers, glacial lakes, and associated moraines can be estimated easily using stereoscopic views and use of high spatial resolution satellite images (Ives et al. 2010).

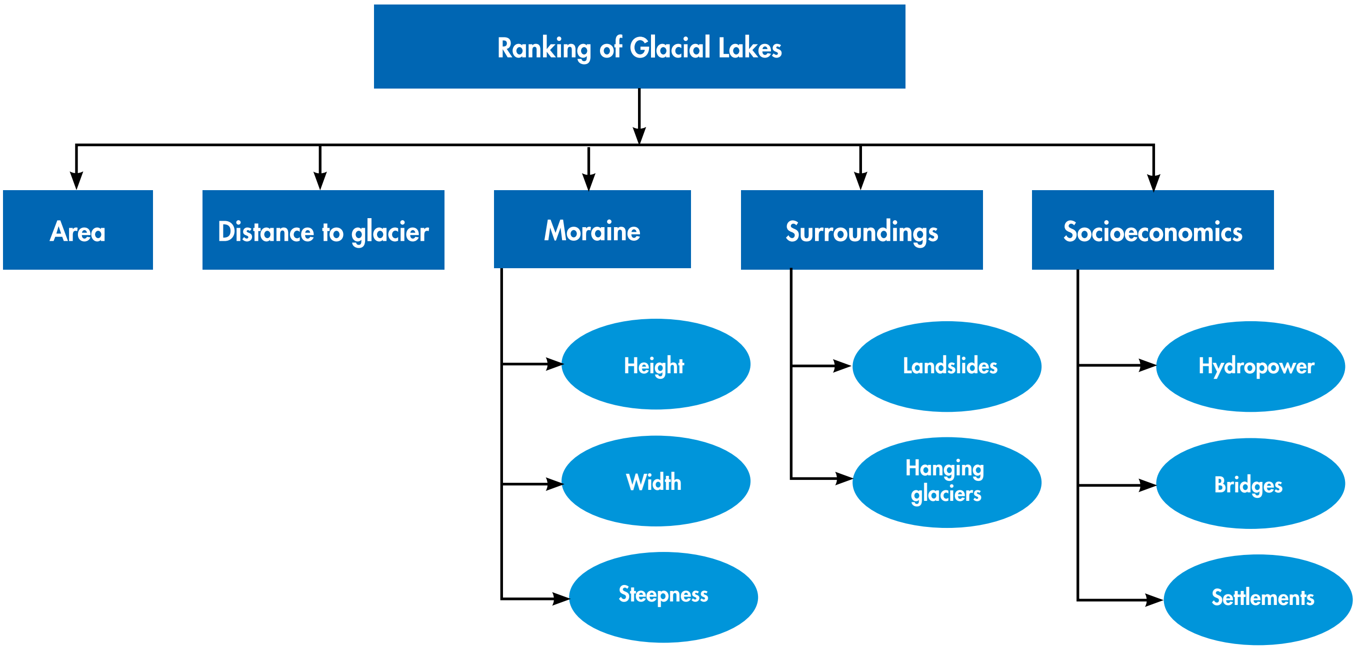
Based on these criteria, 21 lakes were identified as significant.

Prioritisation of critical lakes by ranking

Ranking was carried out for the 21 lakes to determine the priority of lakes for field surveys. Precise ranking was not possible. Heavy reliance was placed on previous GLOF events, however, outbursts can occur that have no historic precedence, especially in view of the current atmospheric warming. It is important to remember this limitation. Also, many of the GLOFs that have occurred have so effectively disrupted the retaining end moraine dams that the likelihood of subsequent outbursts in the same locality is minimal. Another consideration is that where potential outbursts are tentatively identified in areas far remote from human activity, they should not be classed as hazards. Reliable determination of the degree of glacial lake instability, at least in most cases, will require detailed glaciological and geotechnical field investigation (Ives et al. 2010).

As explained above, any attempt to predict the timing and magnitude of GLOF events is problematic. Determining priorities for action to reduce the degree of hazard must also be approached with caution. Because of these difficulties no formal statistical attempt was made to establish the degree of probability of catastrophic lake discharge, and it is not feasible to calculate a unique value to provide a ranking for the implementation of mitigation measures and early warning systems. Rather, the approach taken here was to review several parameters individually and then consider them together. They include the volume of water which could be released; the position of the associated glacier with respect to the lake; the outflow capacity of the lake and the probability for overtopping; the presence of hanging glacier and/or rock falls and other triggers; the stability of the end moraine dams; and the total human and economic losses likely to be incurred downstream in the event of a worst-case scenario. The key physical parameters were taken from those used in the first selection, the socioeconomic parameters were then added to the overall considerations to provide the final ranking. The detailed desk-based approach for ranking was developed and applied to the 21 lakes identified as potentially critical (Figure 5.1).

Figure 5.1: **Physical and socioeconomic criteria used for ranking critical lakes**



Physical parameters

The key physical parameters applied in the ranking were changes in the boundary conditions of the associated glaciers (frontal retreat and thinning) and the lakes (enlargement) over time, and the distance between the lake and the glacier: whether the two were in contact, close, or less than 1500 m apart. Lakes farther than 1500 m from their associated glaciers were not considered potentially dangerous. The rating of the moraine dams included height, width, and steepness. Steepness was rated as follows: very steep (>45 degrees), steep (25 to 45 degrees), or gentle (<25 degrees). Surroundings of the lake area included factors such as possible rock or debris slides, hanging glaciers, and potential avalanche paths.

Socioeconomic parameters

The socioeconomic parameters included the size of downstream settlements (small, <10 houses; medium, 10 to 50 houses; and large, >50 houses), the number and type of bridges (wooden, suspension, motorable, and highway bridges), the distance from hydropower projects (number and capacity of hydropower projects in megawatts), the area of agricultural land in the path of a potential outburst, and any other important infrastructure or activities of economic value such as trekking trails, community service centres such as schools and health centres, religious gathering sites, and camp sites. This information for preliminary assessment was derived from topographic and thematic maps and other secondary sources.

Priorities for further investigation

The socioeconomic and physical parameters were considered together and the critical lakes were categorised into: 1) high priority lakes – requiring extensive field investigation and mapping; 2) medium priority lakes – that require close monitoring and reconnaissance field surveys; and 3) low priority lakes – that warrant periodic observation. Of the 21 lakes reviewed, 6 were classed as Category 1, 4 as Category 2, and 11 as Category 3 (Table 5.1).

Three of the Category 1 lakes were selected for field investigation: Tsho Rolpa, Imja Tsho, and Thulagi Lake. The field investigations are described in the next section of this report. Although the other three lakes merited similar attention, constraints of time and resources mitigated against their inclusion in the present study. The three lakes were selected because they are dammed by a terminal moraine and lateral moraines, and the associated glacier is in direct contact. All have expanded rapidly in the recent past and there is considerable economic activity in the valleys below.

Table 5.1: **List of potentially critical glacial lakes in Nepal identified in the 2010 study and their priority category**

S. No.	Lake ID Number (2009)	Lake Name	Category
1	kotak_gl_0009	Tsho Rolpa	I
2	koaru_gl_0009	Lower Barun	I
3	kodud_gl_0184	Imja Tsho	I
4	kodud_gl_0036	Lumding	I
5	kodud_gl_0242	West Chamjang	I
6	gamar_gl_0018	Thulagi (Dona)	I
7	kotam_gl_0133	Nagma	II
8	kodud_gl_0241	Hungu	II
9	kodud_gl_0193	Tam Pokhari	II
10	kodud_gl_0229	Hungu	II
11	kotam_gl_0191*	–	III
12	gakal_gl_0004*	–	III
13	koaru_gl_0012*	Barun	III
14	kodud_gl_0238*	–	III
15	gabud_gl_0009	–	III
16	kodud_gl_0220	–	III
17	koaru_gl_0016*	–	III
18	gakal_gl_0008	–	III
19	kotam_gl_0111	–	III
20	kodud_gl_0239	East Hungu 2	III
21	gakal_gl_0022	Kaligandaki	III

*Not listed as potentially dangerous in the 2001 inventory

Section 2

Field Investigations and Risk Assessment

End moraine complex of Thulagi glacial lake with unnamed peak in the background, 15 July 2009

6 Field Investigations

Three of the high priority lakes were subjected to intense field investigation. Both the physical conditions and the potential socioeconomic impacts that would result from a possible lake outburst were investigated. This included topographical and bathymetric mapping, hydrometeorological observations, and engineering geological, geophysical, and glaciological research. Potential downstream impacts were estimated using flood-outburst modelling to show which areas would be affected in a worst case situation. This entailed mapping settlements, infrastructure, agricultural land and other features of socioeconomic significance located within the perimeter of the modelled flood limits.

The fieldwork was undertaken between 4 May 2009 and 2 June 2009 for Imja Tsho, 6 July 2009 and 3 August 2009 for Thulagi Lake, and 24 August 2009 and 18 September 2009 for Tsho Rolpa.

The fieldwork was a large-scale undertaking that involved multidisciplinary teams, a wide variety of activities, and the coordination of various government departments, universities, and private institutions. The different sets of activities and the methods employed are described below. A summary of the results is given in Chapter 7.

Areas of Investigation

Stability of the moraine dams

a. Geological and geophysical properties using ground penetrating radar (GPR); this enabled location of buried ice and determination of the composition of morainic materials
b. Moraine geotechnical properties including size distribution, compaction, cohesion and friction coefficients
c. Geomorphological characteristics of the lake and surrounding area
d. Topographical survey of the moraine, the outlet, and the surrounding area including changes in the lake shoreline, and the position of the glacier terminus

Lake storage volume

A detailed bathymetric survey was used to calculate the lake storage volume, using either direct depth measurement or echo-sounding.

Potential external GLOF triggers

a. Observation of the associated glacier for hanging glaciers, glacial retreat, and other phenomena
b. Looking for possible ice avalanches, ice calving, rock and/or debris falls or slides, slope failures, and so on
c. Signs of seismic activity (possible earthquakes)

Hydrometeorological data

a. Measurements of discharge, flow velocity, and cross-sectional area
b. Meteorological data such as air temperature, relative humidity, radiation, wind speed, and direction
c. Electrical conductivity and temperature of the lake water
d. Hydraulic characteristics such as the steepness of the river, channel geometry, roughness coefficient, and seepage information.

Potential socioeconomic impacts

Dam break and flood routing models were calculated to help identify the potential downstream impact areas and elements at risk. The socioeconomic vulnerability was assessed by interviewing the people who lived in the areas identified by the model. The model and the interviews helped to estimate the following:

a. How the moraine dam might fail
b. Peak floods for various scenarios
c. Flood routing downstream
d. Flood hazard mapping and vulnerability assessment (physical)
e. Flood hazard, impact, and vulnerability assessment (socioeconomic)

Field Techniques

Topographical survey

All three lakes were mapped in 2009. This included the end moraines that dam them, together with their overflow channels, the lateral moraines, the lake shorelines, and the glacier termini. Mapping was carried out using a 'total station' (Sokkia and Pentax), a levelling process supported by a differential global positioning system (dGPS) (Leica), and other GPS instruments. The survey used additional benchmarks (BM) installed by different groups during earlier mapping projects to ensure that the resulting map was compatible with earlier maps of the area. Both the existing and newly established benchmarks were used to monitor vertical and horizontal changes in the surface features of the moraines, the lake shoreline, the position of the glacier terminus, and the surroundings over a period of time. Leica dGPS equipment (Leica #SR20, fixed and rover) had been used previously to tie benchmarks to WGS 1984 coordinates. Attempts were made to reconcile field benchmark data with the national WGS 1984 data set (Tsho Rolpa and Thulagi). It is hoped that this will ensure that future work can be tied to the reference benchmarks employed in the present study when the differential global positioning system (dGPS) is not available or not used. The ellipsoidal elevation data obtained from differential calculation of dGPS were corrected by geoid adjustments, which were different for the various geographical locations as per the correction factors of national geodetic survey departments. The WGS 1984 benchmarks for Tsho Rolpa (T1) and Thulagi (G16) were determined by taking several repeat observations and using the mean value. The accuracy of the measured vertical position after repeat observations over three to four hours (battery constraints in cold, high altitudes > 4000m) for several days was two to three metres, whereas the accuracy of the horizontal position was 1-1.5 m for single frequency L1.

The dGPS instrument was used to carry out survey work using the WGS 1984 coordinates with the advantage that these can be referred to and compared in future survey work using common national coordinates. However, the available topographical maps from the Survey Department of Nepal are based on national coordinates, which differ from the WGS 1984 survey. Work with the 'total station' was faster and more reliable (with an accuracy of one second). Observations with the dGPS took longer as there were constraints due to the battery draining within 3 to 4 hrs in the cold narrow valleys and an insufficient number of satellites being available during periods of observation. When elevation differences between two benchmarks were calculated using dGPS, the accuracy of the relative height of the benchmarks improved to 0.5 m.

Bathymetric mapping investigation

The bathymetric survey was carried out from an inflatable boat with an outboard motor. The observations were used to estimate lake storage volume; to evaluate the lake bottom condition near the outlets; and to assess stability of the end moraines below the lake surface. The positions (X and Y coordinates or grid) of the bathymetric observation points were recorded using a GPS. Depth measurements were made using the echo-sounder equipment 'Ninglu DS 2008' in Thulagi and Tsho Rolpa, and an old-fashioned (but effective) method of dropping a weighted line in Imja Tsho (because the echo sounder was malfunctioning). The bathymetric measurements were taken 5 -10 m from shorelines for safety reasons to avoid active sliding of the inner moraine slopes. Bathymetric maps were then prepared and the surface area and storage volume of the lakes were calculated.

Hydrometeorology

DAVIS Automatic Weather stations were installed near the survey camps and operated for the duration of the field studies. This equipment functioned well during the Tsho Rolpa expedition, but malfunctioned at Thulagi Lake and Imja Tsho. Weather data were collected for 16 days at Imja Tsho (11-28 May 2010). Heavy snowfall lasting 36 hours (May 23rd and 24th) caused a loss of precipitation data because the rain gauge was not adapted for snow.

Lake discharge measurements were made using dye tracers and conductivity methods. For the dye tracer study, environmentally neutral sulphorhodamine G (SRG) tracer was introduced into the lake outlet streams for a defined period of time at a constant rate, and water samples were collected downstream at fixed time intervals. The tracer concentrations in the samples were evaluated later in the laboratory using spectro-fluorometry and the results used to calculate discharge. The salt dilution method was used to measure turbulent flow. A salt water solution was poured into the water and, after ensuring homogeneous mixing, electrical conductivity measurements were made at downstream locations at regular intervals to evaluate the salt concentrations – the discharge was then calculated.

Engineering geology and geophysics

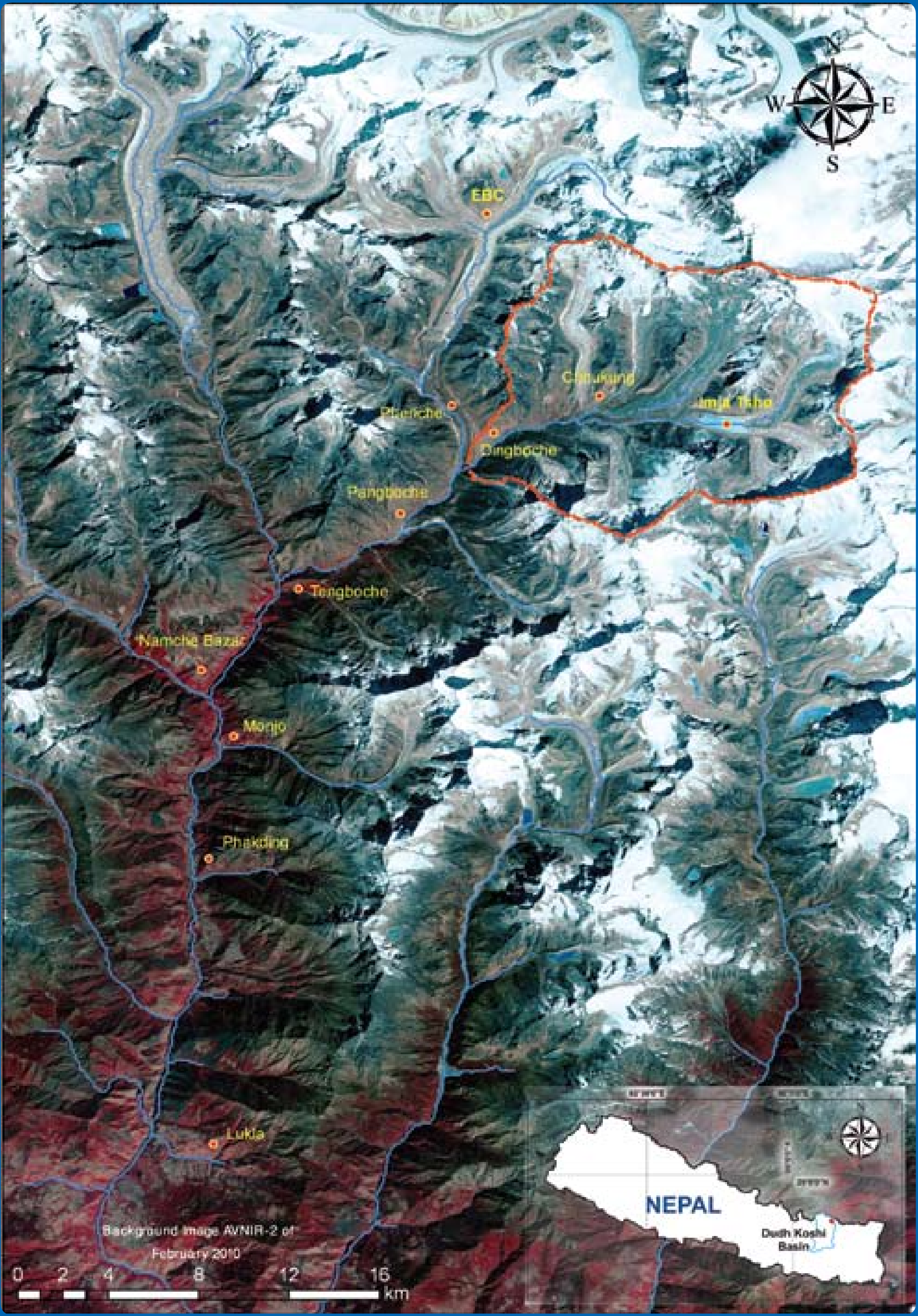
Engineering geological studies were carried out to evaluate the geological settings of the glacial lakes, glaciers, moraines, and the surrounding area. The composition of rocks as well as geological and geomorphological processes and landforms were evaluated. Various landforms, and processes were also analysed. The property of the surface material was estimated for d90, d60, and d10, porosity, and void ratios. Unit weights were estimated subjectively. Angles of repose were measured at several slope locations for input into dam stability determinations and GLOF modelling.

Geophysical investigations were carried out for detection of buried ice both within the moraines and below the lakes. A RAMAC GPR instrument with a 100 MHz antenna was used for the GPR surveys. In the rough and unstable field conditions of Tsho Rolpa, wide angle reflection and refraction survey lines were selected. Due to malfunctioning of the GPR equipment and bad weather, only a few measurements were made at Imja Tsho.

Modelling and socioeconomic analysis

A numerical model was used to simulate GLOF flooding in the downstream valleys and to evaluate socioeconomic impacts for vulnerability assessments. Details of the methodology are provided in Chapters 8 and 9.

Figure 7.1: **Location of Imja Tsho and drainage area of the Imja Khola**



7 Results of the Field Investigations

The results of the field investigations of the three glacial lakes are presented below for each lake individually, and then discussed together in a summary section. All results from previous research were reviewed prior to the field visits. This pre-existing knowledge is presented as a preamble to each section.

Imja Tsho

Imja Tsho is located in the eastern Nepal Himalayas at 27°54′ N latitude and 86°56′ E longitude. It has formed on the lower tongue of the Imja Glacier, south of Lhotse (8,501 m) and Island Peak (Imjatse) (6,173 m) (Figures 7.1 and 7.2).The lake surface lies close to 5,000 metres above sea level. It is drained through the end moraine that forms the lake dam by the Imja Khola, one of the main tributaries of the Dudh Khosi.

An unusually heavy and unseasonal snowfall hampered the fieldwork which was also beset by the malfunctioning of the GPR (ground penetrating radar), automatic weather station (AWS), and echo-sounding equipment. Despite these problems sufficient information was collected to satisfy the expedition's original objectives.

Development of Imja Tsho

Several studies have been carried out on Imja Tsho and its downstream areas (Hammond 1988; Yamada 1992; Watanabe 1992; Watanabe et al. 1994, 2009, 2011; Kettelmann and Watanabe 1998; DHM 2001a, 2001b; Sakai et al. 2005, GEN 2006). The lake was first referred to in the literature by Vuichard and Zimmermann (1987) who used the name 'Pareshaya Tsho', although the derivation of this is not known. Hammond (1988) referred to it as 'the Imja Glacier lake'. This became 'Imja Glacier Lake' (Watanabe et al.1994). It was mentioned as 'Imja Cho' in the topographic map prepared by the Survey Department of Government of Nepal. There was some reluctance to use the term Imja Tsho, or Imja Lake, because neither variation had been formally approved by the relevant Nepalese authority, but both have since come into common usage by default. This minutiae of toponymic detail is included because Imja Tsho has attracted almost world-wide attention due to its assumed extreme danger.

Ground photographs taken in the 1950s demonstrate that, except for several small melt ponds on the glacier surface, no lake existed at that time. The photographs were originally credited to Professor Fritz Müller who served as the 'scientific wing' of the 1956 Swiss Expedition to Everest and Lhotse and who was responsible for the first glaciological research in the Khumbu; however, they may have been taken by Erwin Schneider who was responsible for the first 1:50,000 map of the Mount Everest region. (The accreditation is obscured by the fact that Schneider loaned Müller his photo-theodolite; the theodolite was definitely used to take the photographs of the Imja Glacier, but this does not clearly identify the photographer.)

By 1984 a lake of approximately 0.4 sq.km had formed. The first major step was the acquisition of high quality stereoscopic photographs of the Imja Glacier. They were obtained on the special flight missions directed by Dr Bradford Washburn and Dr Barry Bishop as part of the production process for the 1988 1:50,000 map of the Mount Everest region sponsored by the National Geographic Society. Dr Washburn provided Professor Ives with copies of the stereo-pair and this prompted the systematic collection of all available photographs so that the history of the development of the lake could be documented. Several valuable photographs were provided by Professor K Higuchi of Nagoya University who had led a series of Japanese glaciological expeditions to the Khumbu from the 1960s to the 1980s. The photographs were made available to Ms June Hammond, a graduate student who analysed them as part of the work for her Master's thesis (Hammond 1988). For the first time, it was possible to draw a series of maps that could demonstrate the progressive evolution of the 1956 melt-ponds to a significant and potentially threatening lake by 1984. Since that time there has been continuing research on the Imja Tsho that continues to the present day. The main results are summarised below.

Figure 7.2: **Overview of Imja Tsho showing the lake (centre), outlet channel, ponds, side valleys, and surroundings 24 April 2009**

Watanabe undertook fieldwork in the upper Imja Khola as part of the research for his doctoral dissertation (Watanabe 1992). He continued field observations together with colleagues from Hokkaido University and subsequently with Dr Alton Byers up to the time this report went into production (Watanabe et al. 1994, 2009, 2011). Yamada (1992) directed field research on Imja Tsho (25 March to 12 April 1992) as part of a Japan International Cooperation Agency (JICA) and WECS technical cooperation agreement. Concurrent research by Sakai et al. (2003; 2005) added additional knowledge about the lake's enlargement, its bathymetry, its total volume in different years, and the condition of its end and lateral moraines. Imja Tsho also became part of ICIMOD's large-scale remote-sensing survey and inventory of glaciers and glacial lakes in Nepal (Mool et al. 2001a). Hambrey et al. (2008) studied the characteristics of four glaciers in the Khumbu region, including Imja Glacier and Lake. Watanabe et al. (2009) produced a detailed contour map, together with reconstruction of variations in lake level between 1964 and 2006-2009. By 2006 the previous rapid enlargement of the lake westward towards its end moraine dam had slowed to as little as six metres a year; but it continued to expand rapidly eastward as the glacier terminus retreated. Its total length in 2009 was calculated at 2.2 km (Watanabe et al. 2009).

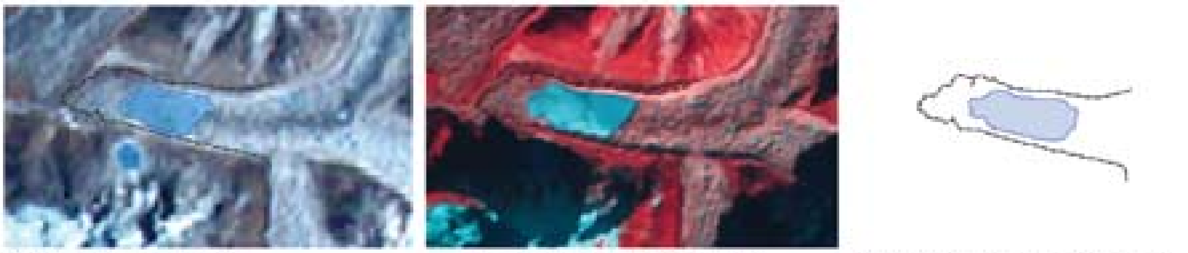
During the early stages of the research discussed above, partly because of incomplete geophysical data, and partly because of the apparently alarming rate of its expansion, Imja Tsho was considered to be in danger of catastrophic outburst. As more data became available, however, particularly the observations showing a major reduction in the rate of lake expansion westwards into the end moraine and other data demonstrating that the lake level had dropped by 37 metres (between 1964 and 2006), the danger of outburst came to be regarded as far less than originally expected.

The field investigations reported here showed a further increase in lake area to 1.012 sq.km.

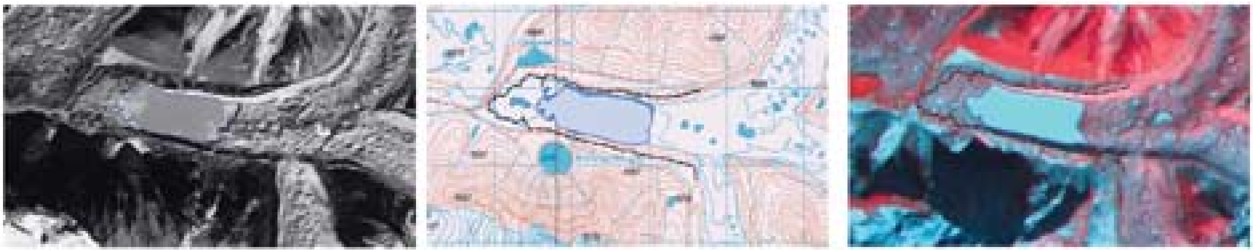
Figure 7.3 shows the progressive development of Imja Tsho between 1962 and 2010.

Figure 7.3: **Development of Imja Tsho from 1962 to 2010 based on Corona (1962) images, Topographical Map (1967), Landsat MSS (Oct 1975), Landsat TM (April 1984, Dec 1989), Aerial photo (1992), LISS 3 (Jan 1999), Landsat ETM+ (Oct 2001, Nov 2005), ALOS PRISM (2006), AVNIR-2 (Nov 2007, Nov 2008, and Mar 2009), Field Survey (WECS 1992, DHM 1997, GEN 2002 and ICIMOD 2009), and EO1_ALI (USGS) Oct 2010)**

15 December 1962, Corona Image — 1967, Survey of India Topographic Map — 15 October 1975, Landsat MSS



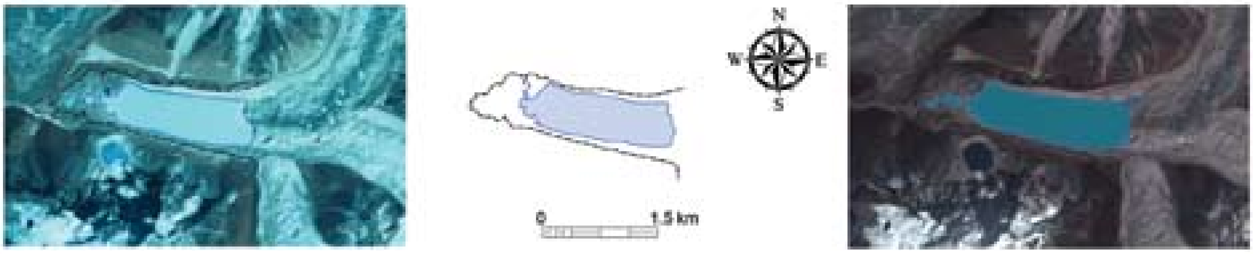
9 April 1984, Landsat 4 — 11 December 1989, Landsat5 TM — April 1992, Field Survey WECS



20 October 1992, Aerial Photo — July 1997, Field Survey GEN/DHM — 15 January 1999, LISS-3

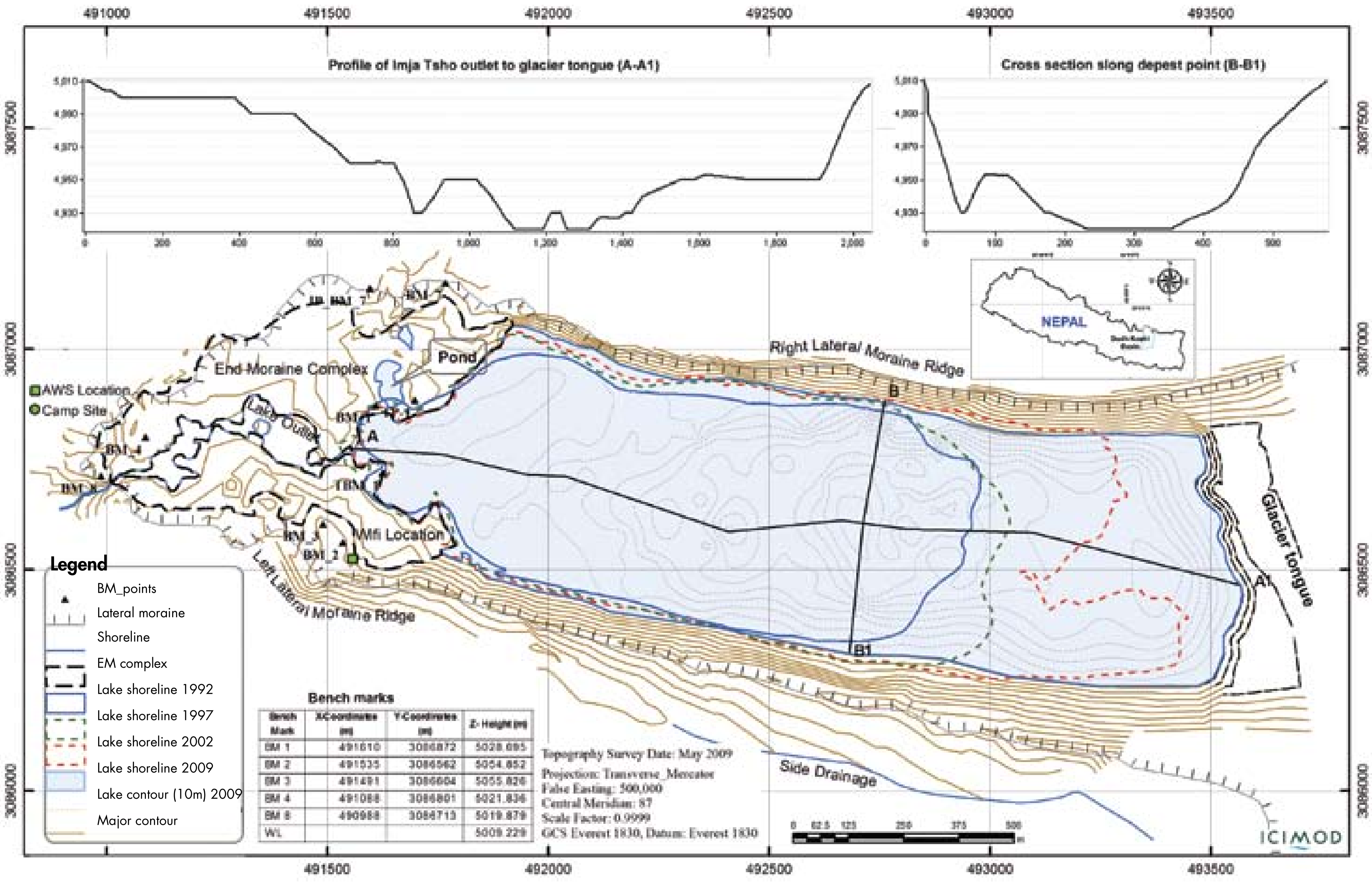
October 2001, Landsat ETM+ — April 2002, Field Survey GEN — 5 November 2005, Landsat ETM+

4 December 2006, ALOS PRISM — 20 November 2007, AVNIR-2 — 24 November 2008, AVNIR-2



17 March 2009, AVNIR-2 — May 2009, Field Survey ICIMOD — 4 October 2010, EO1_ALI (USGS)

Figure 7.4: **Bathymetric and topographic map of Imja Tsho showing the longitudinal profile and cross-section along the deepest point**



Bench marks

Bench Mark	X-Coordinates (m)	Y-Coordinates (m)	Z- Height (m)
BM 1	491610	3086872	5028.685
BM 2	491535	3086562	5054.852
BM 3	491491	3086604	5055.826
BM 4	491088	3086801	5021.836
BM 8	490988	3086713	5019.879
WL			5009.229

Bathymetric investigations

The first bathymetric investigation of Imja Tsho was conducted by Yamada in 1992 under the WECS/Japan International Cooperation Agency (JICA) technical cooperation research expedition (Yamada 1992).

In 1992 the lake area was 0.60 sq.km and its volume 28 x10^6 cu.m (Yamada 1992). The field investigations showed that by 2009 the lake area had increased to 1.01 sq.km and the storage capacity to 35.5 x10^6 cu.m; the maximum depth obtained was 96.5 m. The bathymetric and topographic maps from the field survey are shown in Figure 7.4. The lake area continues to increase, but with a reduction in the rate of growth since 2001. At the same time, the actual level of the lake fell by 0.3 to 0.4 m/yr between 2001 and 2009, while benchmarks towards the end moraine subsided by about 0.1 m/yr (GEN 2006 and ICIMOD Field Survey 2009). The level differences between the benchmarks on the lateral moraines are becoming less, although not uniformly, indicating irregular settling of the surface of the moraine dam over the last seven to eight years.

The contemporary expansion of Imja Tsho is primarily towards the east as the relatively warm lake water melts back into the glacier and accentuates the collapse of blocks of ice from the cliffs that form its terminus. (Yamada 1992; DHM 2001a; Sakai et al. 2005; GEN 2006; and present study). The western margin of the lake close to the end moraine has also expanded, although the position of the outlet has remained more or less unchanged. Watanabe et al. (1994) reported a rapid westward expansion towards the end moraine between 1989 and 1994. Shifting of the outlet channel was also reported (Watanabe 2009). This is not supported by Yamada (1992) nor by the present field investigation, and no significant change between 1992 and 2009 can be detected from the satellite images (Figure 7.4).

Hydrometeorology

The nearest hydrometeorological station to Imja Tsho is located in Dingboche Village about 10 km to the west and 700 m lower in elevation. The station was established in 1988 by the Department of Hydrology and Meteorology (DHM), Government of Nepal. Hydrometeorological data were semi-automatically recorded until 1999 and manually thereafter. Imja Tsho drains through the 500-metre extent of end moraine to form the Imja Khola (river). Experimental measurements showed that the lake discharged at a rate of 0.4 cumecs during the month of May with little diurnal variation. A seasonal maximum discharge of 5.2 cumecs was observed between June and September and a seasonal minimum of 1.1 cumecs between December and February (measured at Dingboche). The discharge increased gradually from April to August and decreased from September until the onset of the winter season.

Meteorological data were obtained from the Dingboche station for the period from 1987 to 2004. The average annual mean temperature for this period was -0.8°C; with an average annual increase of 0.07°C.

August is the month with highest rainfall followed by July. The average precipitation in the area during the monsoon period (June - September) is 273.4 mm and during the dry season (December - February) 13.1 mm. Maximum primary and secondary solar radiation of 267 W/m^2 and 265 W/m^2 were recorded during July and May respectively.

Geophysical investigations

The geophysical investigations showed the existence of dead-ice blocks within the end moraine, together with multiple thermokarst features. In places the ice was visible at the surface. The presence of slowly melting blocks of ice has been corroborated by Yamada (1998a) and Reynolds (2006) who demonstrated the presence of dead ice masses of different sizes in the end moraine. Hambrey et al. (2008) came to a similar conclusion based on geotechnical surveys. Limited radarogram analysis based on a ground penetrating radar survey along the shoreline of Imja Tsho showed that the moraine contains patches of unconsolidated materials made up of big boulders that create large voids.

Glacier observations

Lhotse Shar, Imja, and Amphulapcha are the glaciers associated with Imja Tsho. Lhotse Shar Glacier flows southwestward from the south face of a high mountain ridge dominated by Peak 38, due east of Lhotse (8,501 m) and Lhotse Shar (8,386 m). The Imja Glacier is oriented slightly north of due west; it originates on the northwest face of Baruntse (7,168 m) and coalesces with Lhotse Shar Glacier. Amphulapcha Glacier flows due north and is barely connected with its two neighbouring glaciers. Imja Glacier is heavily covered with debris and has a gentle gradient in its lower section. In the 1960s, its total length was about 10.8 km; this had been reduced to to 8.4 km by 2001, giving a rate of retreat, excluding the dead-ice/ lake section, of 59 m/yr between 1960 and 2001 and of 74 m/yr from 2001 to 2006 (Bajracharya et al. 2007). Its ablation zone faces west. The lower section of the glacier ends in ice cliffs about 40 to 45 m high overlooking the lake. There are numerous crevasses and collapse features (Figure 7.5). The collapse features are thought to be related to the high melting rate of the glacier tongue due to strong solar radiation, the presence of supra-glacial melt-ponds, and the very slow flow rate of the glacier. Periodically, ice calves from the terminal cliff and drops into the encroaching lake. At the opposite end of the lake, the melting of ice blocks within the end moraine is thought to be slow because of the existence of isolated ponds of clear water. Watanabe et al. (2009) examined the condition of the lake outlet channel and considered it to be fairly stable.

Discussion

During the field investigation, inspection of the surroundings showed that there is little possibility of a rock-fall or rock-slope failure that could threaten the stability of the lake. The end moraine damming the lake is 536 m wide and 567 m long; any overtopping waves would have to overcome this wide barrier. The waves generated when ice calving occurs at the fractured glacier terminus are not considered sufficiently large to overtop this terminal moraine. Surge waves were observed following calving from the glacier terminus during the field investigations; by the time they reached the end moraine they were only around half a metre high. The possibility of an ice avalanche into the lake that could trigger a GLOF is also not considered to be very likely at present. In general, the outer slopes of the lateral moraines are gentler than the inner slopes and are abutted by parallel push moraines, wide lateral moraines, or vegetation cover. The inner sides of the lateral moraines that contain Imja Tsho are steep and highly eroded, hence loose sediment falls down into the lake.

The lateral moraines become narrower and lower towards the west as the end moraine is approached and the lake becomes wider. Hence, regular monitoring of the lateral moraines is essential. We recommend that especially the right lateral moraine

Figure 7.5: **Imja glacier terminus from a distance** (below 24 May 2009) **and closer view** (above right 23 May 2009) **showing thick debris cover and numerous transverse crevasses and collapse features**

be monitored because some portions of it are at risk of breaching since they are comparatively narrow and low and contain unconsolidated material. It is also important to note that the end moraine is subsiding as the buried ice melts, and this melting leaves behind coarse materials and potentially large voids which could also reduce stability. Further study is required to assess the likelihood of a larger than expected icefall from the glacier terminus and the potential impact of the resultant surge. In other parts of the world, temporary blockage of lake outlets through moraines due to freezing water and snow barriers or lake ice debris have led on several occasions to outbursts or related hazards. At Imja Tsho, the flow from the lake is uninterrupted, even though it freezes during the winter and an ice layer up to 70 cm thick is formed on the lake itself. This was determined from bore holes during the earlier bathymetric survey (GEN 2006).

The peak outflow from Imja Tsho during the monsoon is accommodated by the existing outlet, although it is not known how much is contributed by glacier melt and how much by local drainage. The present outlet channel is long and wide and flows through the end moraine, but is narrow when it leaves the end moraine complex.

A thorough investigation of the moraine condition is required in order to identify appropriate mitigation measures and whether they are needed. The lake and surroundings, especially the lake outlet, also need to be monitored. This should include discharge from the outlet, any seepage flows from the end and lateral moraines, and contributions from glacial meltwater and englacial flow. Regular bathymetric observation is also needed, including measurement of absolute ground movement to assess moraine dam stability.

Further detailed ground penetrating radar (GPR) investigations are required around the end and lateral moraines of Imja Tsho as there are many exposed thermokarst features along the channel which will play a role in determining the stability of the moraine. The possibility of linking any mitigation measures that might be undertaken in the future to development of a small hydroelectric facility to supply energy to downstream settlements should be considered (this would require hydro-engineering expertise). Such a linkage should be a good way to incorporate input from the local people and would strengthen the protection afforded by early warning systems.

Tsho Rolpa

Tsho Rolpa is located in the central Nepal Himalayas at 27°52′ N latitude and 86°28′ E longitude, at an altitude of 4,546 masl. It forms the headwaters of Rolwaling Khola, a tributary of the Tama Koshi river in Dolakha district (Figure 7.6).

The 1991 GLOF from Chubung (a small supra-glacial lake on the surface of the Ripimoshar glacier adjacent to Tsho Rolpa) alarmed local communities because of the damage it caused 10 km downstream at Bedding village in Rolwaling valley. In 1992, R J de Meijer and E M Smit made a layman's assessment of the hazard of the potential outbreak from Tsho Rolpa (Meijer and Smit 1992). Damen (1992) carried out the first scientific investigations of Tsho Rolpa and made recommendations for measures to lower the water level and to monitor water-level fluctuations. Following the publication of this report, the local community continued to be concerned. WECS led a preliminary field study of Tsho Rolpa with assistance from JICA from 1993 to 1997 (WECS 1993, 1994, 1995, a, b, d, e, 1996, Yamada 1993, 1998; RGSL1994, 1996, 1997; Mool 1995). This was followed by several other studies carried out by professionals and students from different countries on various aspects of Tsho Rolpa. The results were summarised in a number of publications, e.g., Modder and van Olden (1995), Reynolds Geosciences Ltd (1994, 1996, 1997), Mool (1995), Budhathoki et al. (1996), Chikita et al. (1997), and Yamada (1993, 1998). In addition, since Tsho Rolpa was considered to be a potential threat to the Khimti Hydroelectric Project, which was then under construction, it was also studied by engineers from the hydroelectricity project between 1994 and 1996.

Development of Tsho Rolpa

Development of Tsho Rolpa is shown in Figure 7.7. During the late1950s, Tsho Rolpa existed only as a group of six small supra-glacial ponds. Between 1957 and 1959 its area was about 0.23 sq.km. The lake grew continuously from the beginning of the 1960s and by the 1990s it had enlarged to such an extent that it was considered to be on the verge of breeching its end moraine. Satellite images (MOS1 MESSR) showed that it had grown to 1.27 sq.km by 1990 and 1.55 sq.km by 1999. Mitigation work was completed in 2000; this included construction of a gated outlet channel that

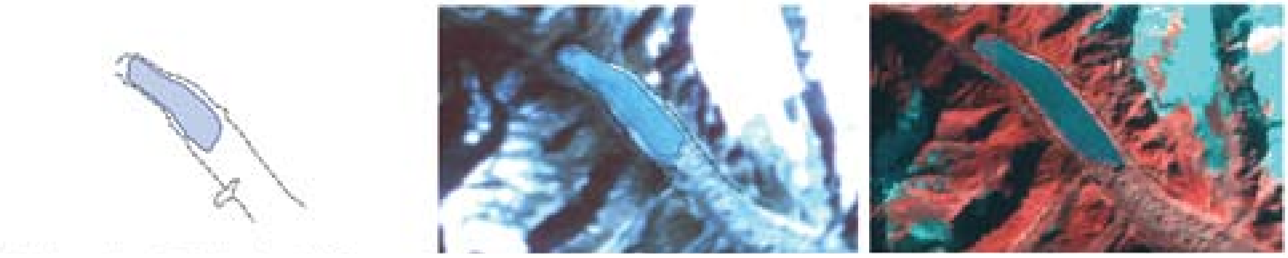
Figure 7.6: **Location of Tsho Rolpa showing catchments of Rolwaling valley and major settlements along the Tama Koshi and Rolwaling valleys**

Figure 7.7: **Development of Tsho Rolpa from 1957 to 2009 based on Topography Map (1957-59), Schneider Map (1960-68), Corona (1973), Landsat MSS (1975), SpaceLab IR (1983), Landsat TM (1991), Aerial Photo (1992), LISS-3 (1999), Landsat ETM+ (2000), AVNIR-2 (2007), WECS Field Survey (1993-94) and ICIMOD (2009)**

1957-59, Survey of India Topography Map

1960 - 68, Schneider Map

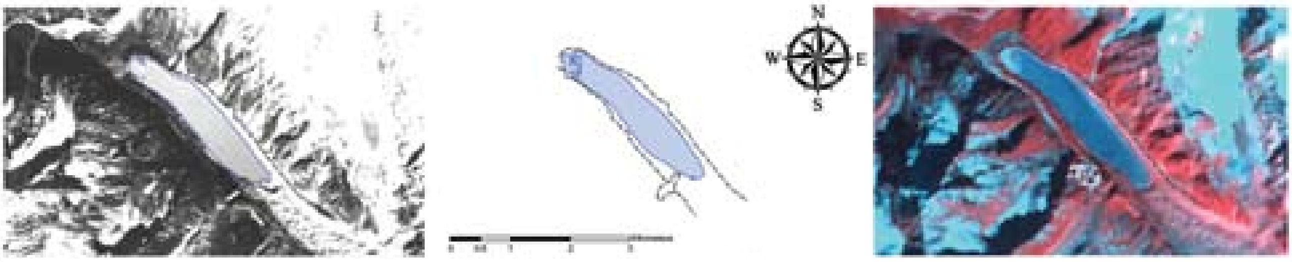
21 November 1973, Corona Image



2 November 1975, Landsat MSS

2 December 1983, SpaceLab IR

17 December 1991, Landsat TM



20 October 1992, Aerial Photo

1993-94, Field Survey WECS

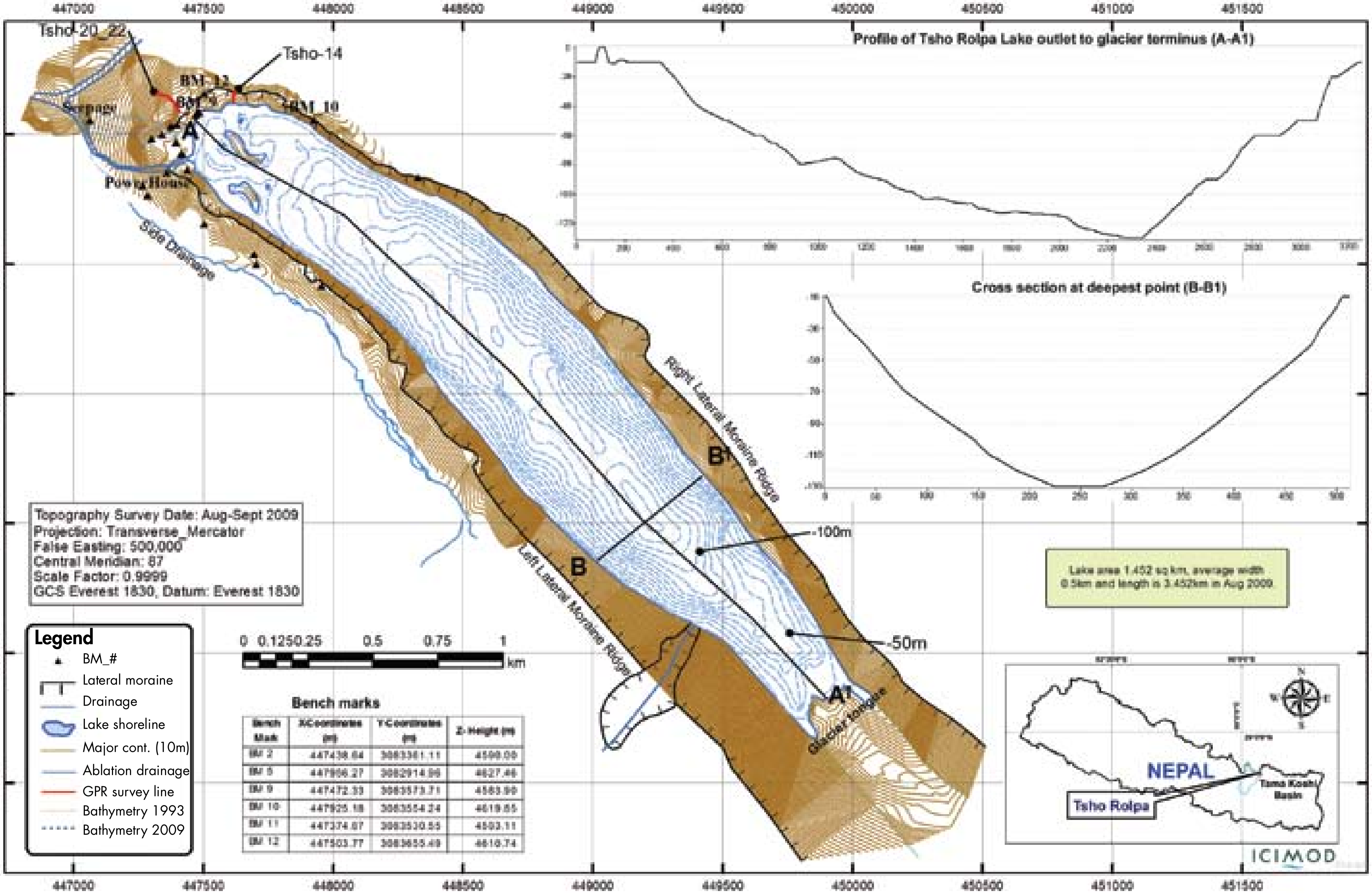
15 January 1999, LISS-3

30 October 2000, Landsat ETM+

19 January 2007, AVNIR-2

August 2009, Field Survey ICIMOD

Figure 7.8: **Bathymetric and topographic map of Tsho Rolpa showing the longitudinal profile and cross-section through the deepest point**



Bench marks

Bench Mark	X-Coordinates (m)	Y-Coordinates (m)	Z-Height (m)
BM 2	447438.64	3083361.11	4590.09
BM 5	447906.27	3082914.96	4627.46
BM 9	447472.33	3083573.71	4583.90
BM 10	447925.18	3083554.24	4619.65
BM 11	447374.07	3083530.55	4593.11
BM 12	447503.77	3083655.49	4610.74

reduced the lake level by three metres. As a result, by 2000, satellite images (Landsat ETM+ 2000) showed that the area had decreased to 1.53 sq. km. Growth of the lake after 2000 was slow. The 2005 satellite image (Landsat ETM+ 2005) indicated an area of 1.535 sq.km and the 2007satellite image (AVNIR-2) an area of 1.538 sq.km. Tsho Rolpa is thought to be one of the most dangerous lakes in Nepal; it is continuously monitored by the Department of Hydrology and Meteorology (DHM).

The current field investigations indicated a length of 3.45 km and an area of 1.537 sq.km.

Bathymetric investigations

Bathymetric investigations of Tsho Rolpa began with the work of WECS in 1993 and have been repeated by a number of investigators since (WECS 1993; 1994; 1995 d; 1996; Yamada 1998a; and DHM 2002 a, b, 2003 b, 2004; Shrestha et al. 2004).

The field investigations showed that the lake has progressively deepened (Figure 7.8). The rate of deepening between Lama Island and Instrument Island was estimated to be 0.234 m/year by Chikita et al. (1997), while Sakai et al. (2000) provided a figure of 0.255 m/year. Comparison of unpublished field data from WECS 1993 and 1994 and field data from the current investigation showed that benchmarks at Lama Island, Instrument Island, and Middle Island are sinking at 0.24 m/year, 0.61 m/year, and 0.49 m/year respectively. The rate of sinking increases from northwest to southeast across the end moraine with an average rate of 0.44 m/year. The deepest part of the lake is sinking at approximately 0.37 m/year, and the average lake deepening rate (including islands and deepest points) is about 0.43 m/year.

Hydrometeorology

Meteorological data are available for Tsho Rolpa for the period from 1993-1996 (Yamada 1998a) but there is a data gap for a considerable part of 1993-94. Unpublished meteorological data for 1999-2004 from the Department of Hydrology and Meteorology, Nepal, were also used for hydrometeorological analysis. Based on these data sources, the daily average air temperature in the Tsho Rolpa area from 1993 to 2004 was estimated to be 0.3°C, with an increase in mean annual air temperature (MAAT) of 0.074° C between 1998 and 2004. This trend is similar to that determined for the Imja Tsho area. The lack of long-term data makes it impossible to predict future trends.

On average, more than 60% of the annual rainfall in the Tsho Rolpa area occurs during the monsoon period from mid-June to mid-September. In the period 1993-2004, the maximum annual precipitation was 829 mm (2004) and the minimum 355 mm (1993). The annual mean solar radiation was 269 W/m^2 in 1994 and 237.6 W/m^2 in 1995. The minimum solar radiation is in December/January (recorded monthly mean 158-180 W/m^2) and the maximum in May just before the monsoon season (356-364 W/m^2) (Yamada 1998a). Yamada (1998a) describes the winds in Tsho Rolpa as quite stable with daily mean values of 1.7 to 2.9 m/s throughout the year.

The capacity of the Tsho Rolpa artificial outlet channel is 35 cumecs, which is roughly twice the maximum monsoon discharge of 18 cumecs measured by the automatic weather station in 1993-94. The maximum and minimum discharge values measured from 1-12 Sept 2009 during the field investigation were 3.54 and 1.89 cumecs.

The derived empirical relationship (rating equation) between the lake-water level and the measured discharge was

$$Q = \mathrm{Exp}\,(4.428) \times (H-H_0)^{1.655}$$

where, Q is the discharge in cumecs, H is the final height (water-level gauge) in m, and H_0 is the initial height (water-level gauge) in m.

Geophysical investigation

An initial electrical resistivity exploration by WECS detected the existence of dead-ice blocks covered by debris at or near the surface of the end moraine (WECS 1995b). Later measurements showed that the dead ice had since melted down to a level at least 5 to 10 m below the surface (RGSL 2000, DHM 2003a, 2003b).

This finding was corroborated by the (GPR) ground-penetrating radar survey during the current field investigation. The GPR survey showed that the northwestern section of the end moraine near the shoreline (Tsho 20-22 and Tsho 14 in Figure 7.8) contained dead ice between BM 12 and BM 10; the depth of its upper contact lay between 14.5 and 17 m below the surface. In other words, whereas there was ice at or near the surface during the WECS 1994 survey, the ice is now 14.5 -17 m below the surface. There is a transitional zone about 0.5 metre thick exhibiting the characteristics of a moist sandy layer between the debris and dead ice.

The radarogram analysis of the Tsho Rolpa end moraine showed that most of the dead ice cores were located in dry, medium to large grain-size, sediments; the end and lateral moraines consisted of coarse and very coarse unconsolidated materials. Large boulders were found about six metres below the surface and were underlain by medium coarse sediments. The presence of large boulders creates large voids, which is a matter of concern for stability.

Glacier observations

The Trakarding Glacier is in contact with Tsho Rolpa (Figure 7.9). It is a debris-covered glacier, with a debris thickness varying from a few centimetres to tens of metres. The whole length of the Trakarding Glacier lies in the ablation zone; the clean Trambau Glacier, which is fed by snow and ice from Mt. Bigphera Go Shar and Go Nup, feeds the Trakarding Glacier. The Trambau Glacier is oriented towards the south, and then continues flowing northwest as the Trakarding Glacier.

In 1960 the Trakarding glacier was about 22.17 km long. This was reduced to 18.62 km in 2009 as measured in the field studies, giving a retreat rate of about 72.3 m/yr between 1960 and 2009, slightly higher than the rate of 66 m/yr reported for 1957 to 2000 (WECS 1993; Bajracharya and Mool 2005) and of 65.7 m/yr between 1993 and 1994 (Yamada 1998a; Chikita et al. 1997). A comparison of the results of the current field investigation with those of the WECS investigation of 1993 and 1994 showed that the lake had extended by 17 to 20 m/yr since 1993. The terminus of the

Figure 7.9: **Glacier terminus with thick debris cover in contact with the Tsho Rolpa. Thermokarsts are exposed on both the left and right lateral moraines which are also in contact with the glacier terminus, 11 September 2009**

Trakarding glacier descends into the Tsho Rolpa at 4,546 masl. In 1997, there was a nearly vertical ice wall about 30 to 40 m above the lake at the terminus; this has now been reduced to a surface slope towards the lake with a height of only a few metres.

There are three hanging glaciers on Mt. Tsoboje situated high above the right side of Tsho Rolpa. Over the years these have not been considered a serious threat in terms of snow and ice avalanches; nevertheless, it is important to continue monitoring them on a regular basis to assess the possibility of a surge wave being generated by ice falls from the glaciers. The stability of these steep glaciers could not be judged during the current field investigation.

Discussion

Tsho Rolpa has a narrow end moraine in which there is a possibility of piping developing (formation of water channels inside the moraine due to seepage, and leading to instability). This needs to be investigated. Seepage was detected at the toe of the outer wall of the moraine dam, but it was found later that it was not coming from the main lake. Follow up investigations will be needed to identify the source of the seepage which could be the melting of dead ice or from local drainage. Regular monitoring will also be needed as discharge and debris from side valleys drop into the lake.

Temporary blockage of the lake outlet over the moraines by freezing water and snow barriers, or lake ice debris is very unlikely because the lake outlet has a wide artificial channel through the moraine dam that functions as a spillway. During the field investigation, the team noted that the gated artificial outlet channel was functioning satisfactorily, but they also noted vibrations in the anchor blocks as well as subsidence in the gabion walls. These two features should be monitored regularly.

Monitoring of the hanging glaciers and the likelihood of them breaking off is one of the major practical challenges in the hazard assessment of Tsho Rolpa. They are clearly visible as they have a limited area. There is a permanent office building with regular staff at Tsho Rolpa who could be trained to make regular inspections of the hanging glaciers and other changes in the condition of the lake, moraine dam, and vicinity as a part of monitoring measures. Climatic data should be recorded and monitored regularly in the Tsho Rolpa area, particularly extreme climatic events and their impacts.

Thulagi Lake

Thulagi Lake is located in western Nepal at 28°29’ N latitude and 84°29’ E longitude at an altitude of 4,044 masl. The lake lies at the end of the Thulagi Glacier to the southwest of Mount Manaslu in the headwaters of the Dona Khola, a tributary of the Marsyangdi river (Figure 7.10).

Thulagi Lake has attracted much attention because several hydropower projects are planned downstream of it in the Marsyangdi river basin. Two projects – the Marsyangdi Hydropower Project and the Middle Marsyangdi Hydropower Project – have already been commissioned and an Upper Marsyangdi Hydropower Project is in the planning stage.
The first field-based investigation of Thulagi Lake was carried out by WECS in 1995 (WECS 1995 c). It was followed in 1996 by a joint investigation by DHM and the Federal Institute for Geosciences and Natural Resources (BGR), Hannover, Germany (DHM 1997). Additional studies were made in 2000 by the Nepal Electricity Authority (NEA), DHM, and BGR (NEA/DHM/BGR 2001).

Development of Thulagi Lake

Thulagi Lake began to form about 50 years ago when small supra-glacial lakes began to enlarge and coalesce. It is now more than 2 km long. Its development was described by Mool and others in a preliminary report prepared from a field survey carried out in 1995. A comparison between topographical maps of the Survey of India from 1958 and the 1995 WECS field results indicated that the lake area had increased in size from 0.22 to 0.76 sq.km and in length from 0.6 to 1.97 km, but that there was not much change in width (WECS 1995c). The present field investigations showed that from 1995 to 2009, the length of Thulagi Lake had again increased from 1.97 to 2.54 km, and the area from 0.76 to 0.94 sq.km.

The development of the lake since 1990 was calculated using topographic maps, satellite images, and the results of the present and previous field investigations (Figure 7.11). The lake is expanding into the glacier terminus, causing it to retreat and calve (Figure 7.12).

Figure 7.10: **The location of Thulagi Lake, catchment of Dona Khola, and major settlements**

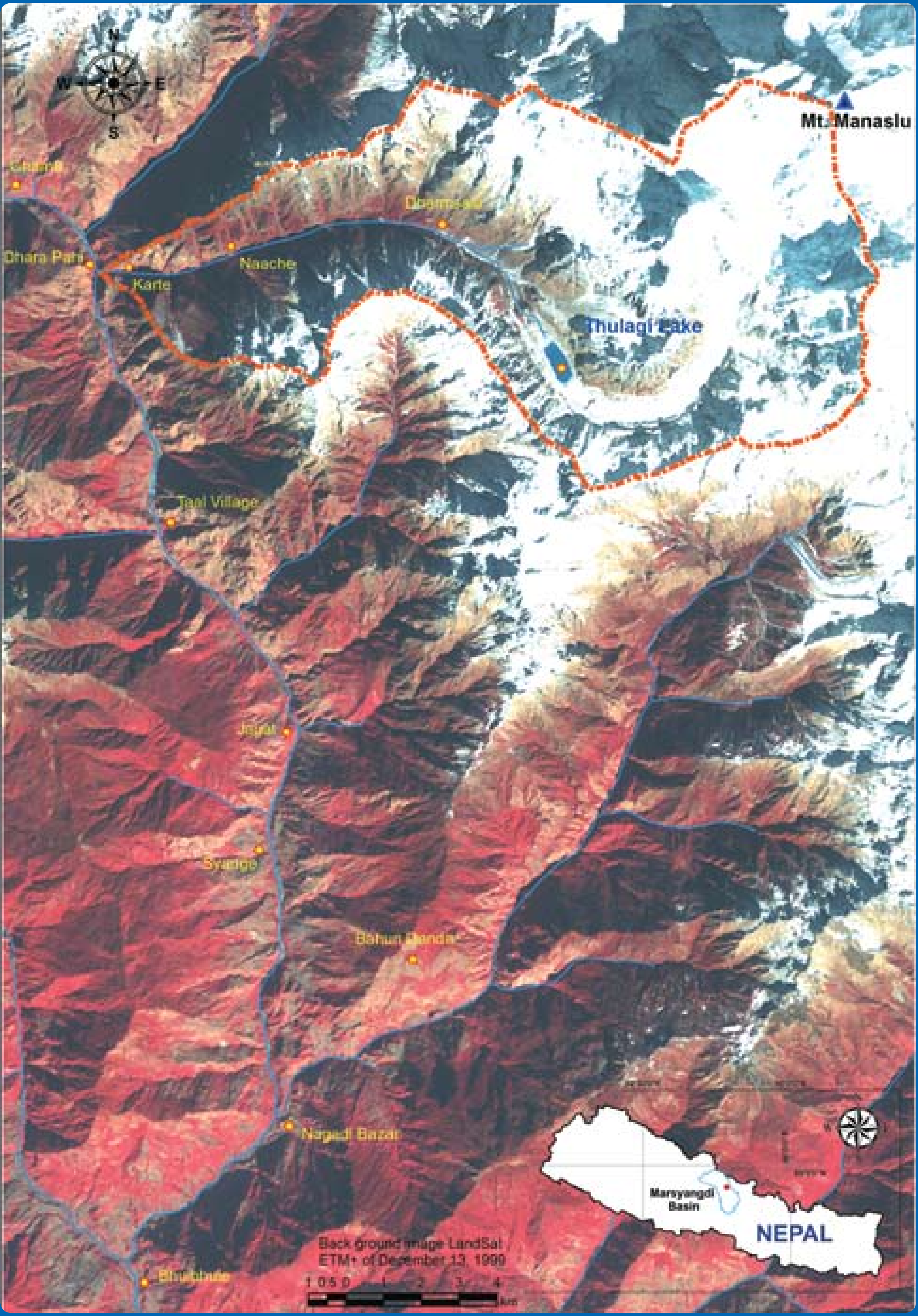
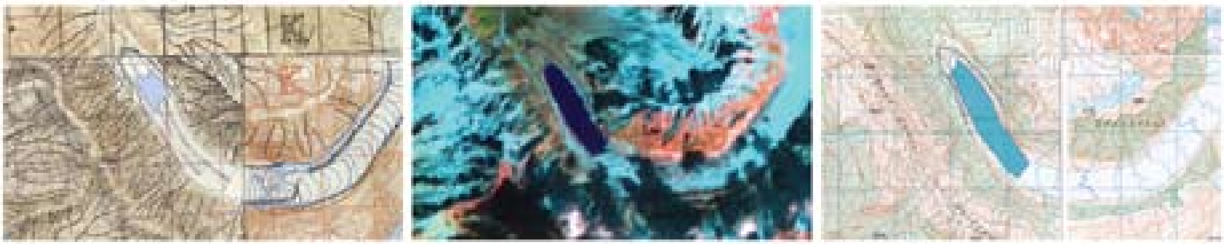


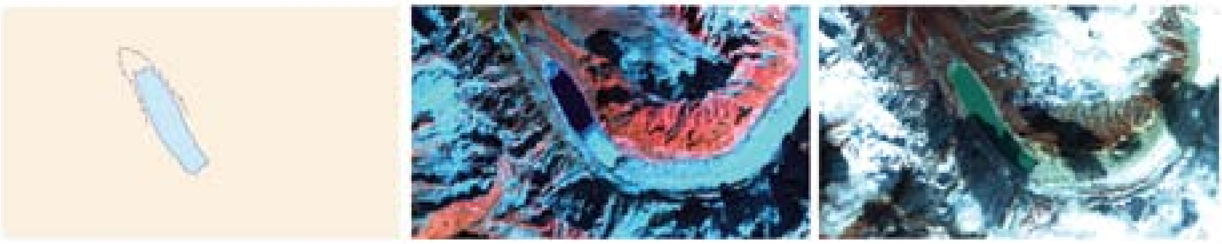
Figure 7.11: **Development of Thulagi Lake between 1960 and 2009 based on the Topographical Map of the Survey of India (1960), Nepal Survey Department (1995), Landsat TM (Nov 1990, Dec 1999), AVNIR-2 (Nov 2006 and Nov 2007), IKONOS-2 (Nov 2009), WECS Field Survey (1995) and ICIMOD (2009)**



1960, Survey of India Topography Map

10 November 1990, Landsat TM

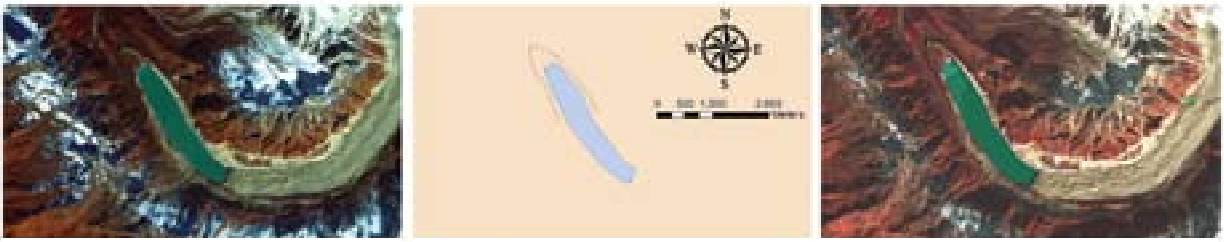
1992 AP based Topography Map, 1995



February 1995, Field Survey WECS

13 December 1999, Landsat TM

10 November 2006, AVNIR-2



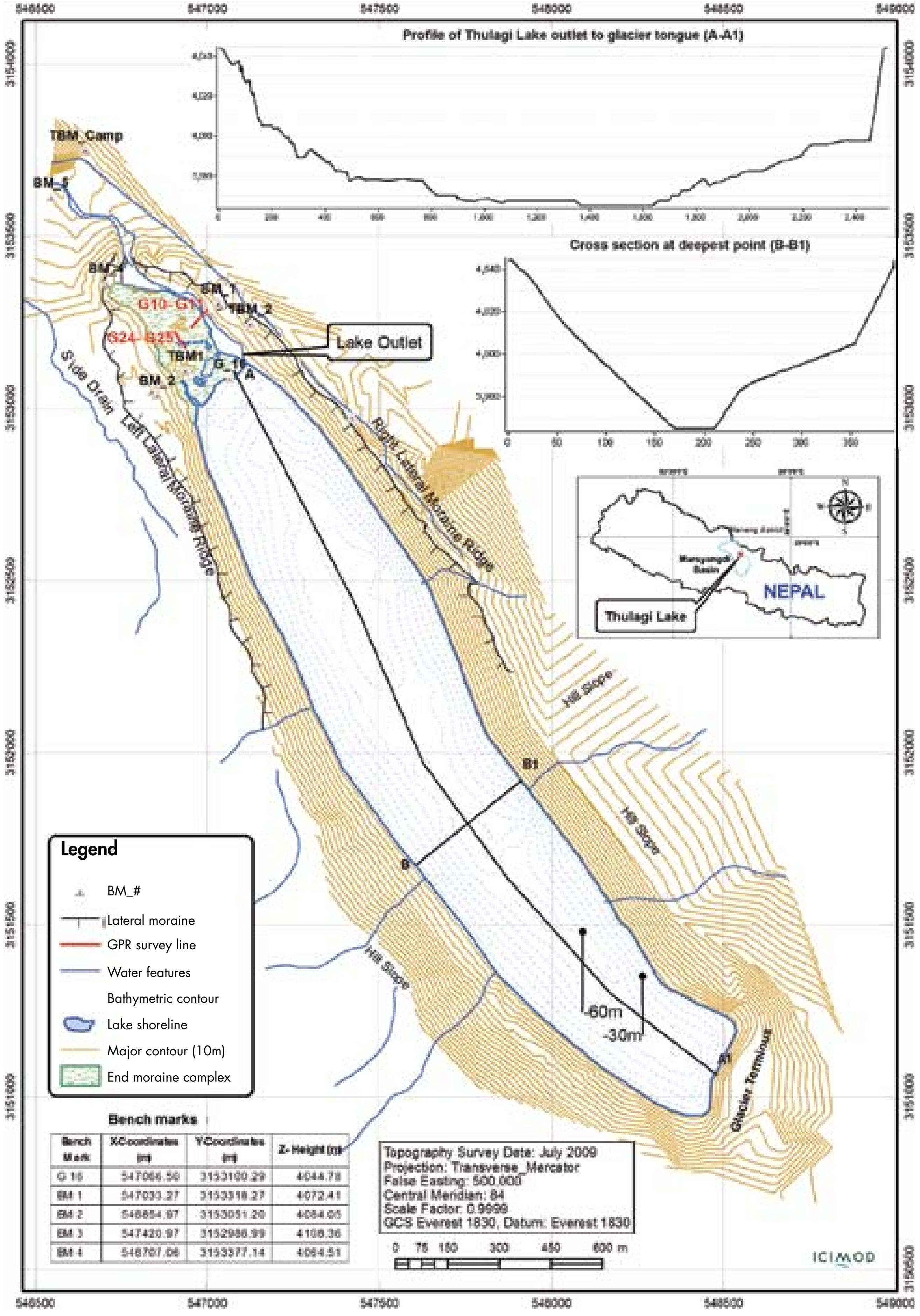
30 November 2007, AVNIR-2

July 2009, Field Survey ICIMOD

14 November 2009, IKONOS-2

Figure 7.12: **Overview of Thulagi Glacier and glacial lake in 1992 photo (left) and 2009 December Quick Bird image (right); the red line shows the expanded area**

Figure 7.13: **Bathymetric and topographical map of Thulagi glacial lake showing the longitudinal profile and cross section along the deepest point. The GPR lines G24-25 and G10-11 show the location of buried ice.**



Bench marks

Bench Mark	X-Coordinates (m)	Y-Coordinates (m)	Z- Height (m)
G 16	547066.50	3153100.29	4044.78
BM 1	547033.27	3153318.27	4072.41
BM 2	546854.97	3153051.20	4084.05
BM 3	547420.97	3152986.99	4108.36
BM 4	546767.06	3153377.14	4084.51

Topography Survey Date: July 2009
Projection: Transverse_Mercator
False Easting: 500,000
Central Meridian: 84
Scale Factor: 0.9999
GCS Everest 1830, Datum: Everest 1830

Bathymetric investigation

Bathymetric survey data for Thulagi Lake were collected by traversing the surface in an inflatable boat with an outboard motor. Figure 7.13 shows the bathymetric and topographic map of Thulagi Lake together with the longitudinal profile and a cross-section at the deepest point. The volume was calculated to be 35.3 x10^6 cu.m, an increase from 31.75 x10^6 cu.m in 1995.

Comparison of benchmarks from previous field surveys by WECS (1995 c), DHM (1997), and NEA/DHM/BGR (2001) with the present field survey (2009) showed that the water level fell 2.18 m between 1996 and 2000 and a further 2.96 m between 2000 and 2009. This implies an average lowering rate of 0.3 to 0.5 m/yr. The lateral moraine walls are also lowering, but at a rate of about 0.1 m/yr: Benchmark 2 (BM 12 in the 2000 survey) on the left lateral moraine subsided by 1.27 m with a horizontal shift of 2.2 m between 2000 and 2009 (Field Data of WECS 1995c; DHM 1997; Field Data 2009). In other words, the moraine dam is sinking more slowly than the lake. The photographs show that between 2000 and 2009, both the lateral and the end moraines subsided and that the outlet channel shifted towards the right lateral moraine (Figure 7.14).

Hydrometeorology

There are no long-term meteorological data available for Thulagi Lake. The nearest meteorological station is located at Dharapani some 2000 m below Thulagi and thus represents quite different climatic conditions. The catchment area of the lake is approximately 56 sq.km of which 55% is covered by ice. It is mainly fed by meltwater from the Thulagi Glacier as well as by other cross-drainage systems. The outlet has a well-developed channel and appears to be stable (Figure 7.15).

Discharge in July 2009 (during the monsoon season) was at a rate of 3 - 4.5 cumecs.

Figure 7.14: **Changes in the shoreline of Thulagi Lake between 1996 (above) and 13 July 2009 (below), show the flow has now shifted towards the right lateral moraine, there are linear subsidence features on the left and right lateral moraines**

Figure 7.15: **The steep Thulagi outlet flowing through a narrow valley, 17 July 2009**

The empirical relationship (rating equation) derived between the lake-water level and the discharge measured at the Dona Khola was:

$Q = \mathrm{Exp}\,(2.996) \times (H\text{-}H_0)^{1.223}$

where Q is the discharge in cumecs, H is the final height (water-level gauge) in m, and H_0 is the initial height (water-level gauge) in m.

Geophysical investigation

An electric resistivity survey indicated the presence of dead ice in the southeastern part of the end moraine damming the lake. The debris-covered segment of the terminal moraine was reported to consist of a 100 m thick body of ice. The shallowest depth for dead ice was about 5- 8 m on the southeast side (DHM 1997; Hanisch et al. 1998; Pant and Reynolds 2000).

The GPR survey during the current field investigation showed that the end and lateral moraines of the lake were made up of coarse and very coarse unconsolidated sediments. A transitional layer exhibiting moist sandy characteristics was identified at a depth of 16.5-17 m below the ground surface towards the western part of the end moraine. At the left bank of the channel, this transitional layer was underlain by buried ice (G24-25 and G10-11 in Figure 7.13). The ice core identified at a depth of 5 - 8 m in the late nineties had melted down to at least 20 m below the surface by 2009. Since the GPR can only penetrate up to a depth of 20 m, the actual depth of the buried ice could not be investigated. The radarogram indicated that larger fractions of sediments are dominant at a depth of about 12-14 m below the surface, where voids are also present. The area of large size sediments is underlain by sediments of medium size.

Glacier observations

The lower part of Thulagi Glacier is covered by debris. Its length decreased from 7.05 km in 1958 (Topographic Survey Map of India, 1960) to 5.38 km in 1999 (Landsat ETM+ 1999) giving a retreat rate of about 40.7 m/yr. Its length has reduced further to 5.03 km by 2009 (ICIMOD Field Survey 2009), a retreat rate of 35.1 m/yr. The glacier exhibits numerous transverse and longitudinal crevasses and collapse features. The collapse features are thought to be related to the rapid melting of the glacier tongue (through strong solar radiation) and its very slow movement. Several ice planes have developed on the lower portion of the ablation area due to longitudinal and transverse creep. There are ice cliffs (about 40 m high) at the glacier terminus and every so often ice calves and falls into the lake (Figure 7.16). The left lateral moraine closer to the glacier terminus contains much loose debris which falls into the lake. Rapid melting is causing the glacier to thin.

Discussion

Thulagi Glacier is a long, debris-covered glacier with a 40 m high terminal cliff. Even though ice calving is a regular phenomena, the surge that these calvings could produce are not deemed sufficiently large to trigger a GLOF event by the surge waves observed during the field study. Temporary blockage of the lake outlet by freezing water and snow barriers, or lake ice debris, appears unlikely, as indicated by the uninterrupted flow of the lake even during winter when the lake surface freezes. Lake drainage continues despite an average ice thickness of 0.4 m, as indicated by bore holes made through the ice during earlier bathymetric observations (WECS 1995c).

The peak monsoon flow from the Thulagi Lake is easily carried by its outlet channel. Regular monitoring is needed, however, to check for exceptional drainage input as discharge and debris from the side valleys, as well as to detect seepage flow and any undermining of the moraine dam.

Meteorological observations are needed to detect both extreme climatic events and annual variations. This could be accomplished by installing an automatic weather system (AWS) where data could be retrieved regularly, recorded, and published for public use.

Figure 7.16: **The Thulagi Glacier terminus in contact with the lake, the glacier tongue is about 40 m high above the water surface and exhibits snow stratigraphy (circle), 22 July 2009**

Summary of the Field Investigations

The key findings of the field investigations of the three lakes relate to the following issues: stability of the moraine dams; lake-storage volumes; GLOF triggering factors; hydrometeorological influences; potential GLOF hazard level; and monitoring, mitigation, and early warning systems.

Stability of the moraine dams

The elevation of Thulagi Lake is almost 1,000 m lower than that of Imja Tsho, which is significant in terms of climate regime and local vegetation. Thulagi had vegetation cover even close to the glacier terminus and surrounding the lake, and trees were growing on the terminal moraine. The outlet channel cuts through the right lateral moraine and its banks are being undercut.

The clasts in the moraine varied widely from pebble to gravel-sized particles in all three lakes, but there were also boulders measuring hundreds of cubic metres. The terminal moraine of the Imja Tsho was hummocky with a profusion of cones, mounds and depressions, whereas the Thulagi moraine was vegetated. Imja Tsho had the largest number and highest density (number per unit area) of sink holes, and they also had the largest radius. Boulders had also created large voids. The end moraine complex of Thulagi Lake displayed numerous small sink holes.

The height of the lateral moraines above the lake surface increased from the lake outlets towards the glacier termini in all three lakes, varying from less than 15 to 30 m near the outlet, to 30 to 50 m towards the middle section of the lake, and 50 to 100 m towards the glacier termini. The inner slopes of the lateral moraines were steeper, highly active, and eroded towards the glacier termini, and less eroded with partial vegetation cover closer to the outlets; this was particularly noticeable at Thulagi Lake. The inside slopes of the lateral moraines were composed of two distinct segments at all three lakes: lower segments inclined at about 30-35° (the angle of repose), and the unstable upper segments inclined at up to 45- 50°. The outer slopes of the lateral moraines were hummocky but stable with comparatively gentler vegetated slopes further strengthened by spur-like push moraines. The outer slopes of the Imja Tsho moraines had comparatively sparse vegetation cover.

The height of the side valleys between lateral moraine and rock slope were not physically measured during the field survey, but they appear to be at a greater elevation than that of the lake surfaces. Thus more emphasis was placed on the condition of the end moraines. In addition, the right lateral moraines of Thulagi Lake and Tsho Rolpa are in contact with bedrock towards the glacier termini. Overall, collapse of the lateral moraines is unlikely, but the lower sections could be more vulnerable to overtopping failures.

At all three lakes, the lateral moraines in contact with the glacier termini had buried ice with thermokarst features. In both Tsho Rolpa and Thulagi, the left lateral moraines also had thick loose debris, with more in Tsho Rolpa than in Thulagi. In both lakes, water enters laterally from the surface of the left lateral moraine.

The end moraine areas of all three lakes had linear cracks (Figure 7.17) that were more pronounced at the junction with the lateral moraines. The steep inner slopes are undercut by the surface currents in the lakes, and are also collapsing gradually as a result of ice melting within the moraine.

Lake growth

The physical characteristics of the three lakes as identified during the field surveys of 2009 are summarised in Table 7.1.

The development of all three lakes began at about the same time through amalgamation of small ponds. The more rapid initial growth of Tsho Rolpa resulted in it becoming the largest moraine-dammed lake in Nepal; Imja Tsho grew faster than Thulagi Lake (Figure 7.18). Tsho Rolpa has the largest storage volume and greatest lake depth (Figure 7.19). All three lakes are moraine-dammed and in contact with their associated glacier, and have thus mainly expanded towards their glacier terminus in parallel with glacial retreat and calving. Over the last decade, the expansion of Tsho Rolpa has been minimal, but Imja Tsho is expanding significantly and the glacier terminus is retreating. Its western section close to the end moraine is widening. The rate of expansion of Thulagi Lake is appreciable slower. The volume of Tsho Rolpa is increasing by an

Figure 7.17: **Contact of the lateral and end moraine complex with extensive linear features and sink holes at Thulagi Lake, 24 July 2009**

Table 7.1: **Comparison of the physical characteristics of the three lakes**

	Dam characteristics			Physical characteristics of the glacial lakes					Expansion rate per year[1]		
Lake	Height (m)	Free board (m)	Width (m)	Length (km)	Area (sq. km)	Storage volume (x10^6 cu.m)	Average depth (m)	Maximum depth (m)	Length (m)	Area (sq.km)	Volume x10^6 cu.m
Imja Tsho	31	10	567	2.03	1.01	35.5	35.1	96.5	42-47	0.0266	0.50
Tsho Rolpa	216	5	50	3.45	1.54	85.94	56.4	133.5	17-20	0.0129	0.26
Thulagi Lake	67	15	340	2.54	0.94	35.37	37.4	79.5	35-41	0.0115	0.53

Note: [1] Expansion rate per year’ denotes values for Imja Tsho between 1992 (Yamada 1992) and 2009 (present study), for Tsho Rolpa between 1993/94 (WECS 1993, 1994) and 2009 (present study), and for Thulagi Lake between 1995 (WECS 1995c) and 2009 (present study)

average of 0.26 million cubic metres per year, and those of Thulagi and Imja by about 0.5 million cubic metres per year (Table 7.1). The water depth of all three lakes increases towards the glacier termini, but here the lateral moraines are 50-100 m in height and either in contact with bedrock or with debris or talus cover. Thus, the lateral hydrostatic pressure exerted by the greater depths are more or less counterbalanced by the lateral moraines, and the expansion of the lakes has not added any extra lateral pressure to the relatively weak moraine at the outlets.

There was no significant expansion of the lakes towards the end moraines apart from the widening of Imja Tsho: the outlet positions have remained more or less unchanged between the 1990s and 2009. The shoreline of Tsho Rolpa has undergone significant changes at the northwest and southeast of the end moraine and islands have submerged between 1993 and 2009. The Thulagi outlet channel had shifted towards the right lateral moraine and seepage and dried ponds were exposed. Changes in shorelines have also occurred in Imja Tsho, where thermokarst features were exposed at several locations.

Figure 7.18: **Comparison of lake development from images, topographical maps, and field investigation data for the Imja Tsho, Tsho Rolpa, and Thulagi Lakes. Imja lake grew at a slower rate up to 2000 when the rate increased; the growth rate of Tsho Rolpa diminished substantially after mitigation in 2000**

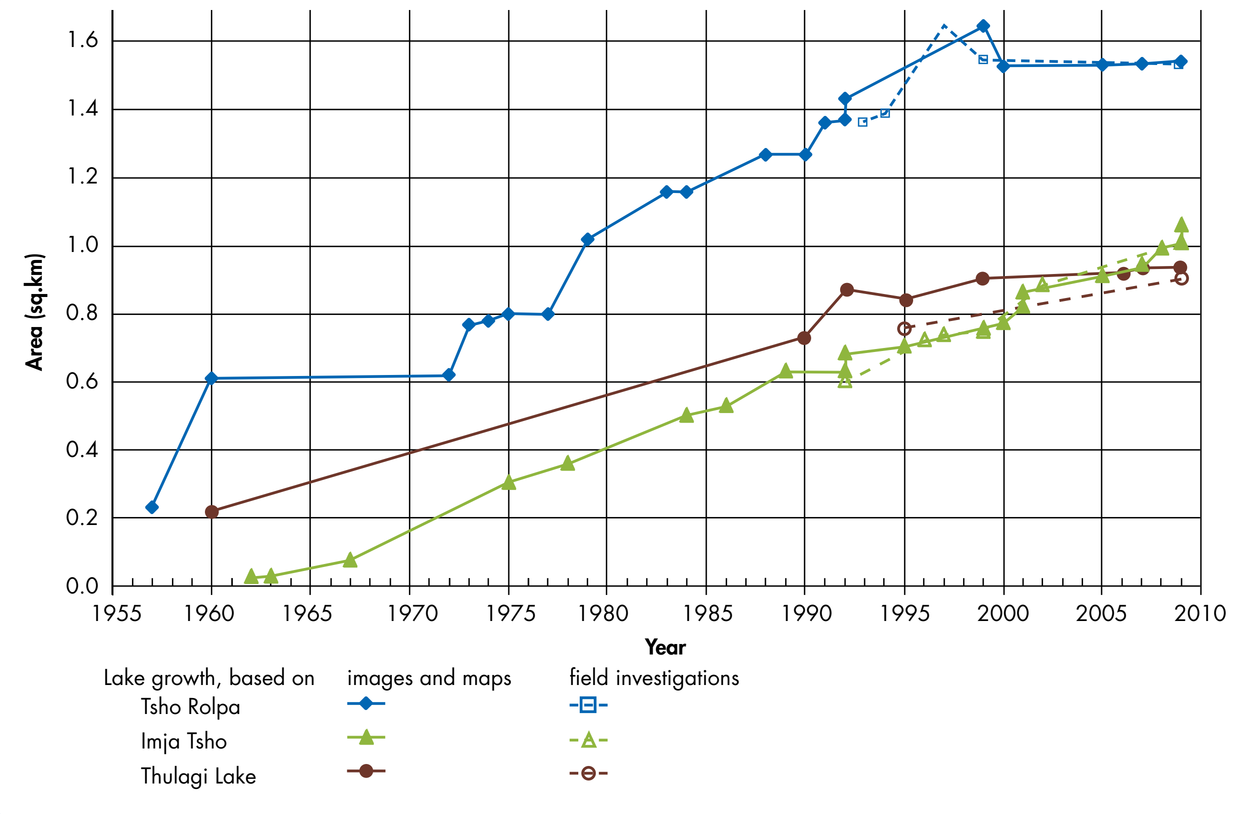
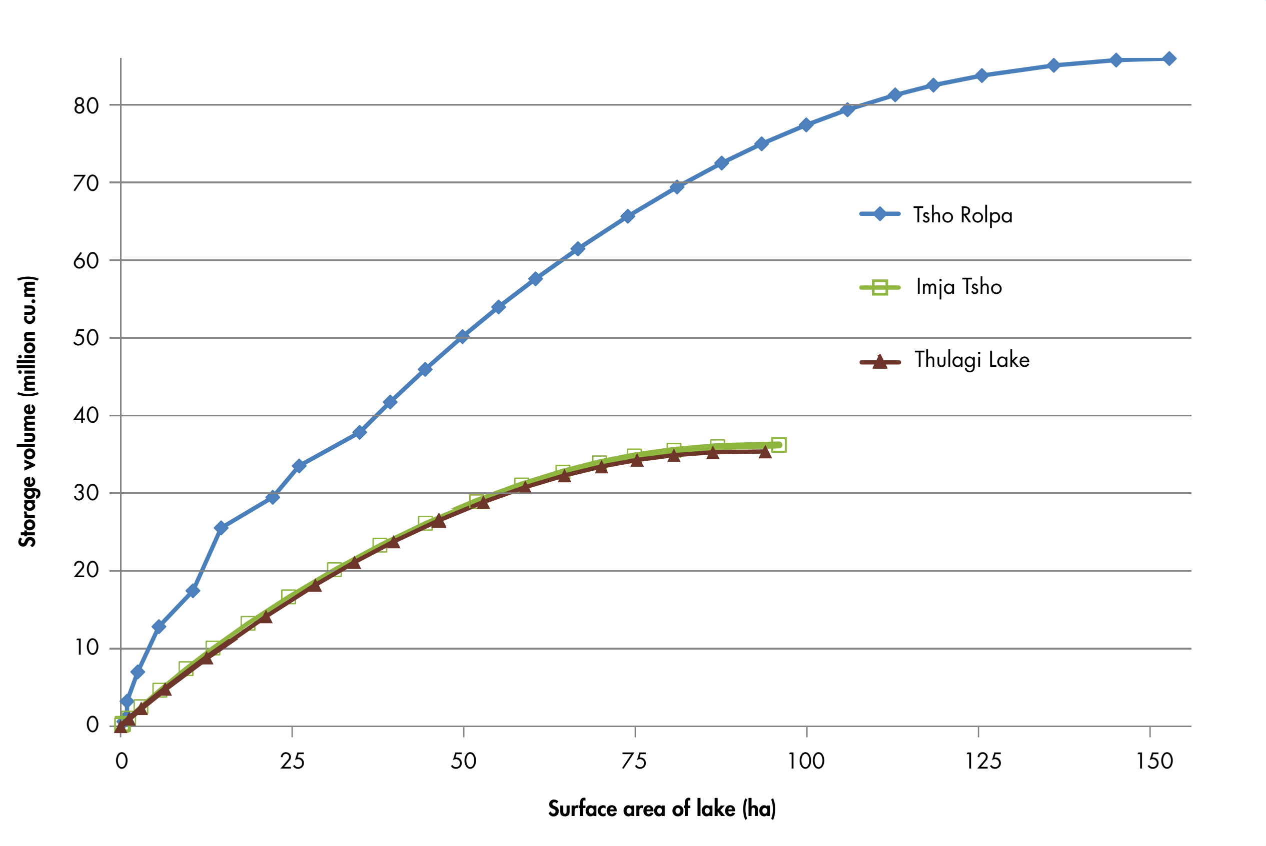


Figure 7.19: **The relationship of volume and depth for the Tsho Rolpa, Thulagi, and Imja lakes.**



GLOF triggers

The ablation areas of the Tsho Rolpa, Thulagi, and Imja glaciers were covered by debris derived mainly from the slopes above. The Imja and Thulagi glaciers have several transverse crevasses (Figures 7.5 and 7.16) and collapse features; they are calving into the lakes, although the collapsing masses of ice are not large enough to generate dangerous displacement waves. In the case of Tsho Rolpa, three hanging glaciers high above on Mt Tsoboje should be monitored for signs of instability as they could potentially produce ice avalanches.

Extreme events such as heavy snowfall or very high temperatures could destabilise the lakes. Earthquakes could also affect moraine and lake stability, however assessment of the potential danger of glacial lake outburst as induced by earthquake tremor is most likely beyond current competence.

Hydrometeorological influences

Hydrometeorological factors such as air temperature, humidity, radiation, wind speed, wind direction, and precipitation influence glacial melt, discharge into the lakes, and melting of buried ice. Because there is no long-term data base or systematic monitoring, understanding of likely impacts is limited.

All three lakes have an effective discharge capacity, hence there has been no significant rise in water levels. Undercutting of moraine slopes is not a substantial threat. In Thulagi Lake, even though there is some undercutting in the channel of the river at the foot of the right side of the end moraine, this effect is balanced out by the decrease in surface level of the lake.

The Trakarding, Thulagi, and Imja glaciers have temperate regimes (at 0°C), at least in their lower sections, and retreat has accelerated as a result of sub-glacial melt flow, sub-aqueous melting of ice (as shown by the lowering of the lake bottoms), and undercutting by water from the lake. Tsho Rolpa has a high concentration of suspended sediment load (Table 7.2).

Table 7.2: **Physical parameters of lake water of Imja Tsho, Tsho Rolpa and Thulagi Lake**

Parameters	Imja Tsho	Tsho Rolpa	Thulagi Lake
Date	May 2009	Sep 2009	July 2009
Conductivity (µS)	410	311	808
Surface water temperature (°C)	2	6.6	9.3
pH	-	6	6.5
Suspended solids (mg/l)	3.6	151.4	4.3

Potential GLOF hazard

The outlets are critical because all three lakes have low freeboards – 5, 10, and 15 m, for Tsho Rolpa, Imja, and Thulagi, respectively.

Tsho Rolpa's storage volume of 86 million cubic metres, dam height of 216 m, lowest freeboard (5 m), and narrow dam cushion, means there is more likelihood of a GLOF occurrence than from Thulagi Lake or Imja Tsho. Thulagi and Imja both have ca. 35 million cubic metres of storage, but considering their dam heights, widths, and freeboards, Imja Tsho has less likelihood of outburst than Thulagi Lake (Table 7.1). However there are many other parameters to be taken into consideration in making further assessment.

Although the lake level of Tsho Rolpa fell by three metres after the mitigation measures were put in place, there is still more likelihood of a GLOF occurring there than from the two other lakes. Tsho Rolpa is vulnerable to overtopping of low magnitude (about 5 m), thus, hanging glaciers, debris flow, or slides on a small scale pose a potential threat. Imja Tsho and Thulagi Lake have higher freeboards of more than 10 m and wider moraines (> 300 m).

All three lakes need to be monitored for seepages which can cause moraine dam failure by piping/undermining. Similarly, other key features including hydrometeorological conditions such as lake water level, excessive drainage, or extreme climatic conditions, and dam conditions such as subsidence or collapse of lateral and terminal moraines and moraine dam crest height and width (particularly for Tsho Rolpa) should also be monitored.

There is a further need to assess the influence of the surroundings, for example the impacts of hanging glaciers (Tsho Rolpa); debris flows/slides (Tsho Rolpa and Thulagi); and the condition of associated glaciers that may generate calving on a scale sufficient to cause a large surge wave. Variation amongst all of these features may influence GLOF hazard levels. Neotectonic activity or earthquake induced GLOF hazard is a possibility that should be considered, although prediction is beyond the current competence.

Overall the findings indicate that the immediate risk of a GLOF occurring is much lower than had been postulated for all three lakes; but many factors cannot be assessed, and catastrophic changes cannot be predicted. Thus there is an urgent need for more information as well as for regular monitoring and early warning systems.

An early warning system (EWS) was established before mitigation work on Tsho Rolpa began, although it is no longer operational. It should either be repaired or a new one installed (see chapter 10). EWS systems should also be installed for Imja Tsho and Thulagi Lake. Low cost EWSs (e.g., code division multiple access-CDMA) should be simple enough for operation and maintenance by the local communities. GLOF sensing and warning systems should give sufficient time for response. Awareness-raising in the local communities about the hazard and necessary response is essential. This recommendation was made by local, research, and government participants during the workshops and the field investigations.

Detailed risk assessment

The results of the field investigations were used in modelling experiments to determine more accurately the likelihood of a GLOF event occurring and the potential for downstream impacts. These detailed assessments are discussed in the following two chapters.

8 GLOF Modelling

Introduction

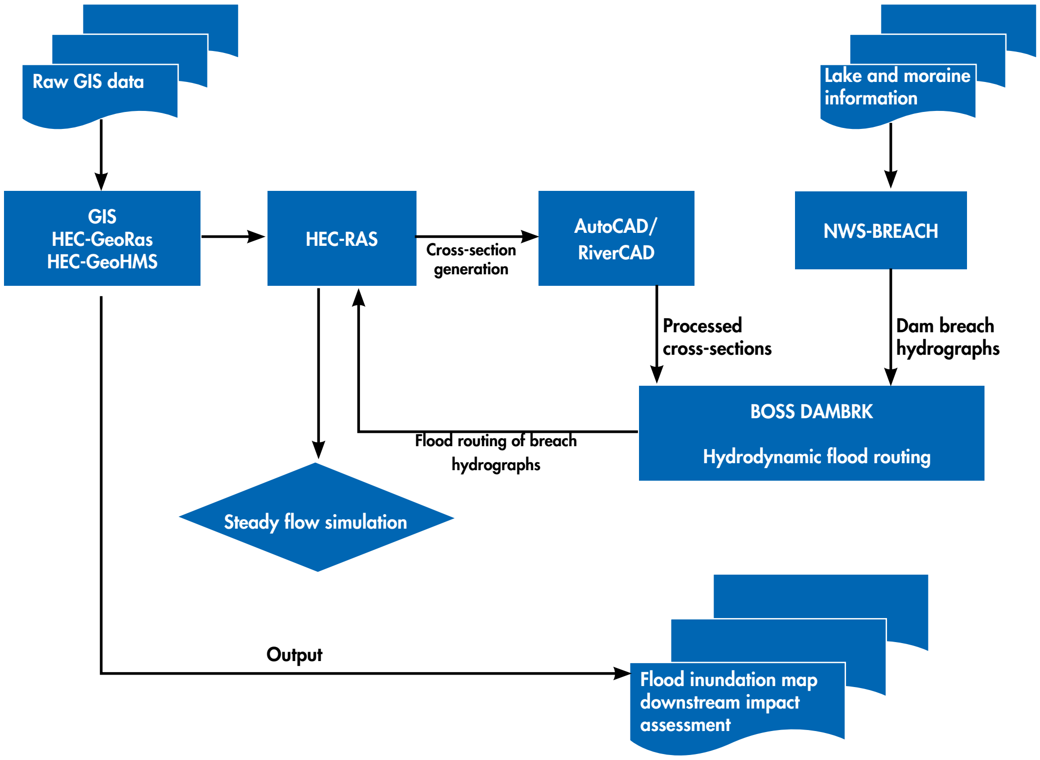
Detailed GLOF hazard and risk assessment is undertaken by simulating GLOF scenarios. Numerical hydrological modelling of the three high priority glacial lakes was carried out using data from the field investigations and from secondary data sources.

A breach model was used to simulate the failure of a dam. The breach hydrograph obtained with the model is simulated for flood routing in the valley downstream. The governing equations used for dam break models were the complete one-dimensional St. Venant equations for unsteady flow using internal boundary equations. Appropriate external boundary equations were used for the upstream and downstream ends of the routing. The hydrograph was specified as an input time series. Selection of breach parameters before a breach forms or in the absence of observations introduces a varying degree of uncertainty in the downstream flooding result of the dam break flood forecasting (DAMBRK) model. Errors in breach description and in the resulting peak outflow rate are damped out, however, as the flood wave advances.

Modelling Objective and Approach

The main objective of GLOF modelling was to simulate moraine dam failure of the high priority lakes and assess potential GLOF impacts downstream. The specific objectives were i) to develop a glacial lake breach model, ii) to develop a model of flood propagation in the valley downstream, iii) to develop a model of inundation in the river valley, iv) to forecast flood arrival time and velocity of flow, and v) to assess downstream GLOF impact. The study was in three stages: i) modelling outbursts; ii) modelling flood propagation downstream and flood mapping; and iii) downstream GLOF impact assessment. Figure 8.1 gives a schematic representation of the study method.

Figure 8.1: **Schematic representation of the methodology used for modelling GLOFs and assessing downstream impacts**



Sources of data

A hydrodynamic modelling approach was applied for GLOF simulation and vulnerability assessment. Topographic information about the study area determines the accuracy and reliability of the model. Spatial data such as a watershed boundary, digital elevation model (DEM) of the study area, drainage network, inline structures of rivers, land use/cover, settlements, infrastructure, and administrative boundaries were derived from the topographic maps of 1992 prepared by the Survey Department of Nepal, and satellite images.

The 2009 field survey provided data about the lakes including the surface area, maximum depth, and top and bottom elevations, and information about moraine dams including the inside/outside slope, dam length and width, unit weight of dam material, porosity, diameter of particles (d90, d50 and d30, at 90, 50, and 30% finer on the grain size distribution curve), and internal friction angle (ϕ). Manning's roughness coefficient n of the outer core of the dam was estimated. Socioeconomic information was obtained from field interviews.

A digital elevation model (DEM) of the study area was prepared; the Hec-GeoHMS modelling package was used to fill sinks and generate rivers for input into cross sections, flow lines were exported to AutoCAD and cross sections imported back to ArcView GIS. Data were exported to HecRAS for pre-processing. The top width and elevation were input into BOSS DAMBRK as breach definition, and lake and moraine dam parameters were input into NWS Breach for dam break analysis: breach hydrographs were generated based upon this (Figure 8.1). The breach hydrographs generated from NWS Breach were routed to BOSS DAMBRK for hydrodynamic flood routing.

The computer applications used for modelling watershed boundaries, river flow, and basin and river properties included ArcGIS/ArcView, HEC-GeoHMS; HEC-HMS; HEC-GeoRAS was used to acquire geometric data sets from the digital terrain model; and NWS-BREACH, BOSS DAMBRK, HECRAS, and AutoCAD/RiverCAD were used for GLOF modelling.

Input Parameters for the Dam-breach Model

The physical parameters of dams derived from field investigations and other sources were used to simulate breaching. The dam geometry and properties of dam material are given in Table 8.1.

Table 8.1: **Geometrical and dam material properties of Tsho Rolpa, Thulagi Lake, and Imja Tsho**

S. No.	Parameters	Unit	Tsho Rolpa	Thulagi Lake	Imja Tsho
1	Lake surface area	sq.km	1.53	0.94	1.01
2	Lake maximum depth	metre (m)	133.5	79.5	96.50
3	Dam top elevation	metre (masl)	4546	4044	5010
4	Dam bottom elevation	metre (masl)	4526	4024	4990
5	Dam inside slope	1:z	1:4	1:4.5	1:2
6	Dam outside slope	1:z	1:3	1:5	1:4
7	Dam crest width	metre (m)	50	20	50
8	Dam crest length	metre (m)	315	305	275
9	Diameter of 90% finer particle (d_{90})	millimetre (mm)	300-600	200-400	800
10	Diameter of 50% finer particle (d_{50})	millimetre (mm)	10[#] (5-15)	20[#] (30-60)	20[#](10-30)
11	Diameter of 30% finer particle (d_{30})	millimetre (mm)	1-4	1-4	2
12	d_{90}/d_{30}		225[#]	150[#]	400[#]
13	Unit weight (γ)	kN/m^3	18[#] (17-20)	18[#] (17-20)	18
14	Porosity	%	30[#] (25-35)	30[#] (25-35)	30
15	Internal friction angle (Ø)	degree	35[#] (30-40)	35[#] (30-40)	38
16	Cohesiveness (c)	kN/m^3	0	0	0

[#] = value adopted in breach model

Modelling Results

Dam-breach analysis and flood simulation

The NWS breach model was used for numerical estimation of breaching times and possible breach peak floods from the three lakes. More than 20 outburst scenarios for each lake were modelled in NWS-BREACH to test the sensitivity of the input parameters and their influence on results.

The breach height for all three lakes was derived as 20 m with breaching times of 0.62, 0.92, and 2.69 hours and peak flows at the time of flow as 7,242; 4,750; and 5,817 cumecs for Tsho Rolpa, Thulagi Lake, and Imja Tsho respectively (Figures 8.2 a, b, and c).

Flood routing

The outburst hydrographs of NWS-BREACH were used in DAMBRK for one-dimensional hydrodynamic flood routing for all three lakes. The potential flood stage, flood wave travel time, time to peak flood stage, and corresponding water surface elevations in downstream areas were calculated. The maximum flow, time to reach maximum flow, and high flood depth at various locations are given in Figures 8.3a, b, c for Tsho Rolpa, Thulagi Lake, and Imja Tsho respectively.

Beding, Suri Dovan, Lamatar, Khimti, and Rajgaun located at 9.6, 40.8, 75.5, 82, and 99.7 km from the Tsho Rolpa outlet, can expect flood arrival times of 0.79, 1.48, 2.76, 3.83, and 5.76 hours, respectively.

Dharapani, Tal, and Nayabasti located at 13.5, 19.2, and 94.1 km from Thulagi Lake outlet, can expect flood arrival times of 0.99, 1.17, and 5.40 hours, respectively.

Dingboche, Pangboche, Benkar, Ghat, and Rabuwa located at 7.97, 15.72, 29.18, 37.34, and 100.2 km from the Imja Tsho outlet, can expect flood arrival times of 3.124, 3.39, 3.8, 4.2, and 7.44 hours, respectively. Because of the wide crest width of Imja moraine dam, breaching takes about three hours as obtained from the NWS breach model; the data about the flood reaching downstream corresponds to the time breaching commences. The highest amount of discharge recorded by the Department of Hydrology and Meteorology, Nepal, at Busti near Nayapul is 2,130 cumecs. (gauge height 7.12 metres) on the 17th August 1998. It is estimated that a discharge caused by a 20 m dam breach in Tsho Rolpa would be about 2,929 cumecs just below Busti; which does not include sediment load or tributary flow data.

Figure 8.2: **Breach hydrograph of a potential breach**

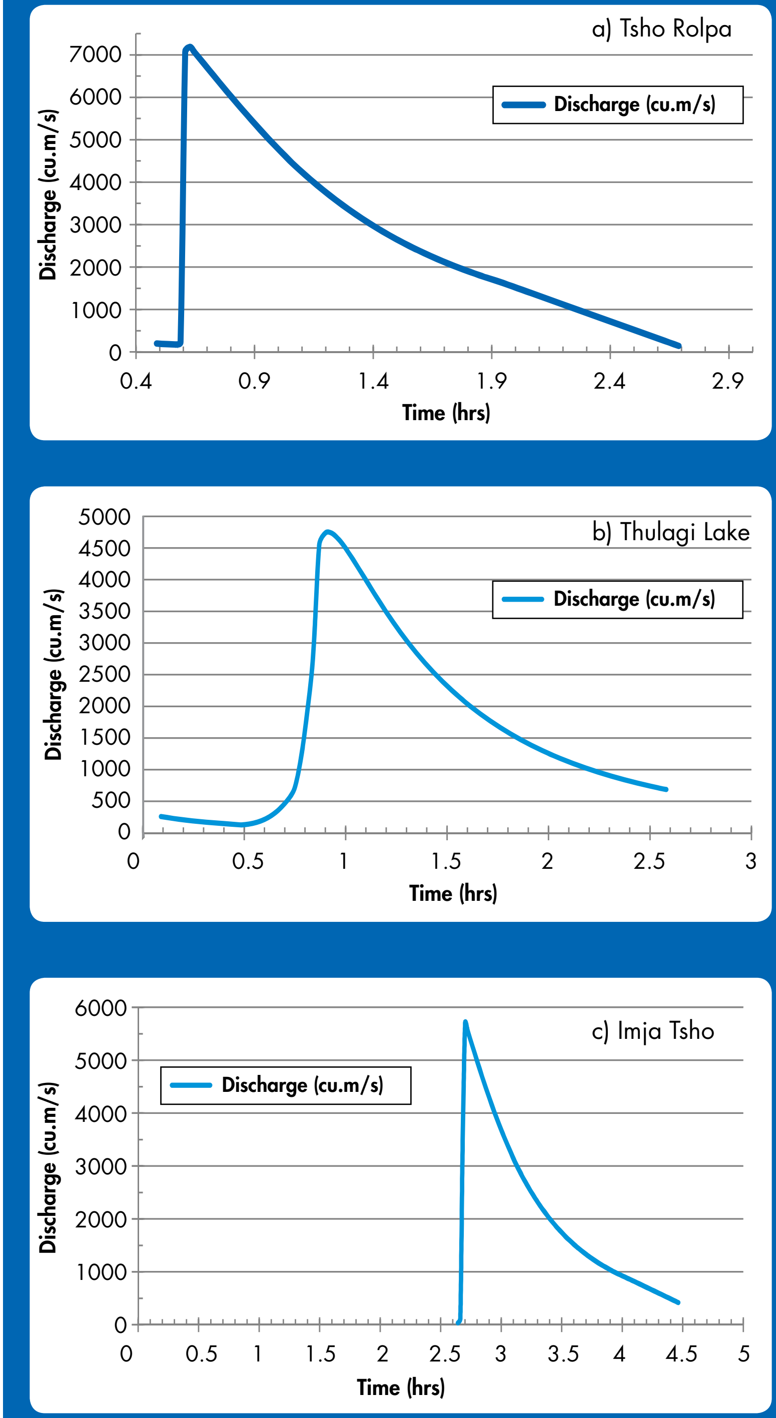
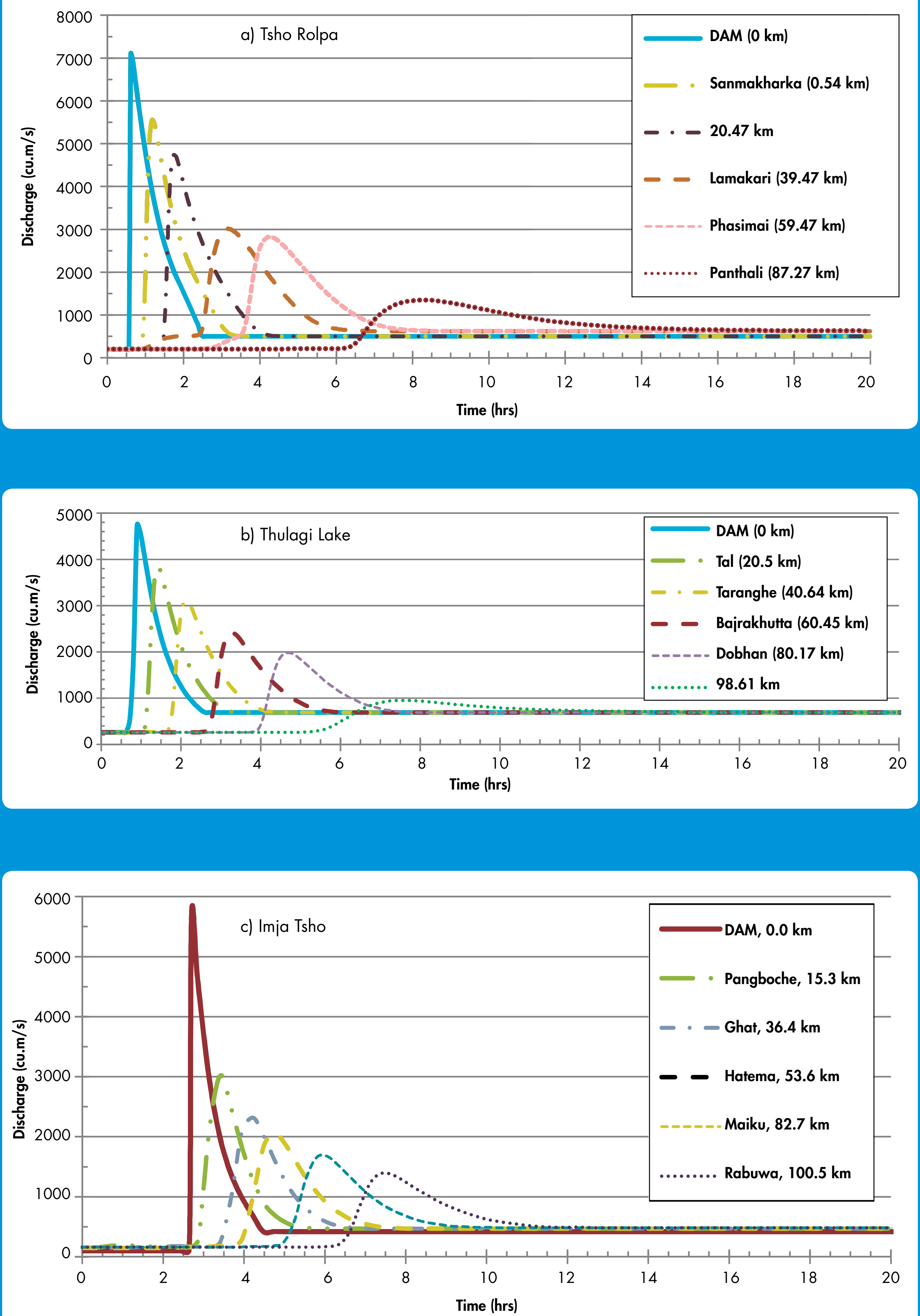


Figure 8.3: **Flood attenuation at various downstream locations**



Peak flow estimation and flood height

Flood routing along the valleys downstream differs among the lakes. Tsho Rolpa's peak flood decreases sharply in stretches, in the initial flow from the dam up to 10 km, then at 40-60 and 90-100 km. Apart from a flat stretch of 60-90 km, the stretches are moderately sharp (Figure 8.4a). Sanmakharka, Beding, Rikhu, Syalu, Suri Dovan, Nayapul, Jujar, and Rajgaun would experience flood heights of more than 10 m.

Flood routing for Thulagi Lake had a systematically decreasing trend in the peak flow with a gradual decrease as it proceeded downstream (Figure 8.4b). Dharapani, Tal, Sattle, Lampata, Dadabagar, Belghari, Naubise, Botgaun, and Nayabasti would receive a flood height of more than 10 m. Tal village located a few metres above the river would be seriously affected as the flood depth above the normal flow depth would be over 7m and all the settlements and land would be damaged.

The peak flood from Imja Tsho decreases sharply within the initial 10 km stretch, with a further gradual decrease beyond 20 km (Figure 8.4c). The potential flood height is less than those of Tsho Rolpa and Thulagi as heights are less than 10 m throughout the valley, even though the peak flood is higher than that of Thulagi Lake. Dingboche, Orse, Ghat, Bupsa, Lap, Phapare, and Kuwapani would receive moderate impacts.

Flood Inundation Maps and Downstream Impacts

Peak discharge and flood heights were calculated with numerical models on the basis of the GLOF modelling to simulate GLOF impacts downstream. Beyond 50 km, the initial peak flood is more or less halved. The areas impacted by either high peak flood or high flood levels were classified as high risk zones, and areas with potentially substantial socioeconomic losses were mapped as highly vulnerable. The (flood) inundation maps were overlaid with the socioeconomic data to assess GLOF vulnerability (Figures 8.5, 8.6, and 8.7).

Land exposed to a potential GLOFs

Possible landcover losses were estimated by overlaying the flood hazard maps on to landcover maps. The results are summarised in Table 8.2.

An estimated 833.2 ha up to about 100 kilometres downstream would be exposed to a GLOF from Tsho Rolpa: about 62% (515.0 ha) would be flooded along the course of the river, 38% would be agricultural land (169.8 ha), forests (68.6 ha), grassland (4.2 ha), shrubland (37.4 ha), and barren land (38.1 ha).

An estimated 1132.8 ha would be exposed to a GLOF from Thulagi Lake: about 73% (821.3 ha) would be flooded along the course of the river; 28% would be agricultural land (188.7 ha), forests (73.9 ha), grassland (33.3 ha), and barren land (15.6 ha).

An estimated 1009 ha would be exposed to a GLOF from Imja Tsho: about 56% (567.0 ha) would be flooded along the course of the river and 44% would be agricultural land (87.6 ha), forest (206.9 ha), grassland (54.1 ha), shrubland (24.1 ha), and barren land (35.8 ha).

Table 8.2: **Land-cover types exposed to potential GLOF risks from the three lakes up to 100 km downstream**

S. No.	Land-cover type*	Tsho Rolpa		Thulagi Lake		Imja Tsho	
		Area (ha)	%	Area (ha)	%	Area (ha)	%
1	Agricultural land	169.8	20.4	188.7	16.7	87.6	8.7
2	Forest	68.6	8.2	73.9	6.5	206.9	20.5
3	Shrubland	37.4	4.5	-	-	24.1	2.4
4	Grass	4.2	0.5	33.3	2.9	54.1	5.4
5	Barren land	38.1	4.6	15.6	1.4	35.8	3.5
6	River course	515.0	61.8	821.3	72.5	567.0	56.1
7	Other	-	-	-	-	34.4	3.4
	Total	**833.2**	**100**	**1132.8**	**100**	**1009.9**	**100**

* Source: ALOS Image, 2009

Figure 8.4: **Peak flood and flood height of the three lakes**

Figure 8.5: **Modelled flood inundation map along the Tama Koshi valley, downstream from Tsho Rolpa**

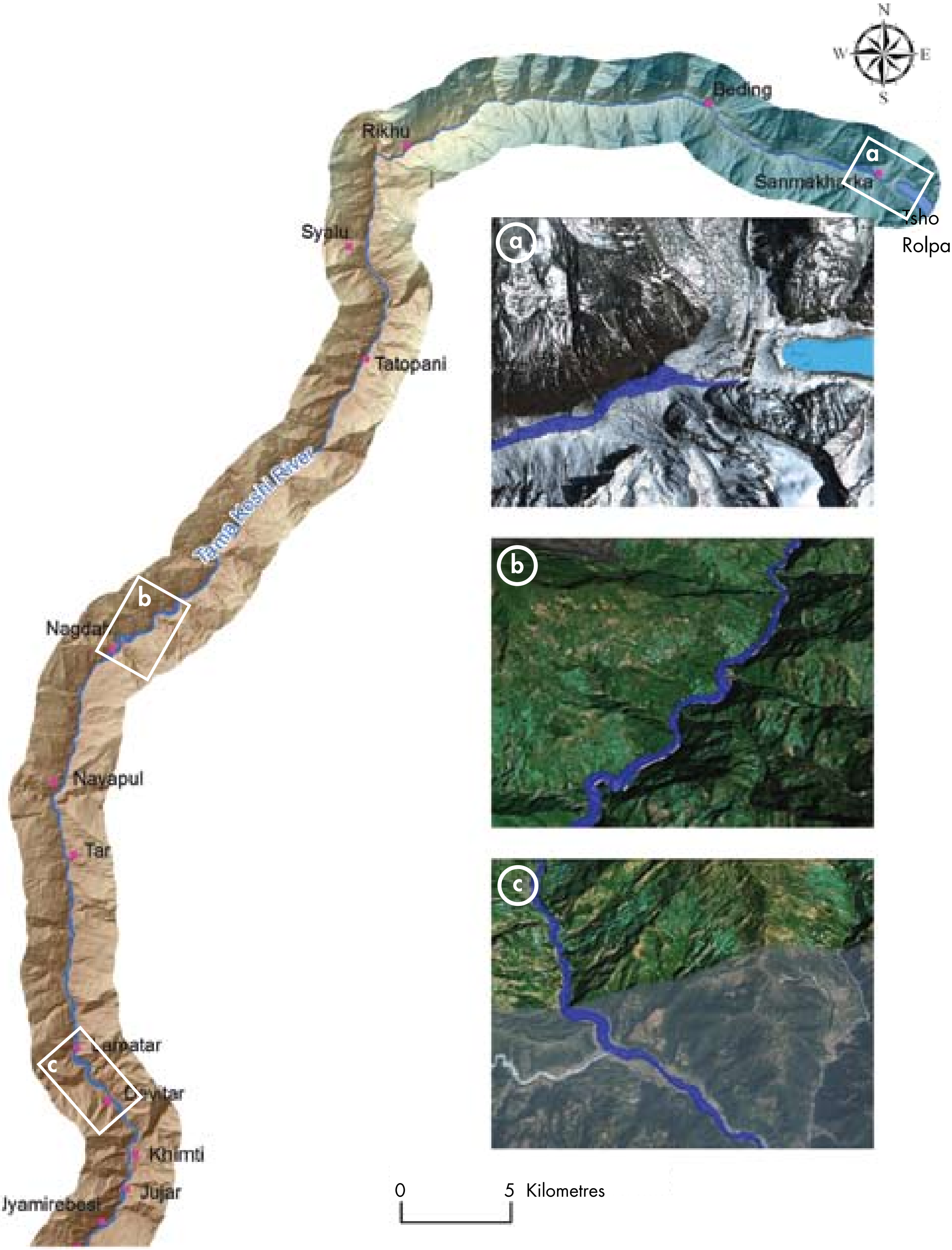


Figure 8.6: **Modelled flood inundation map along the Marsyangdi valley, downstream from Thulagi Lake**

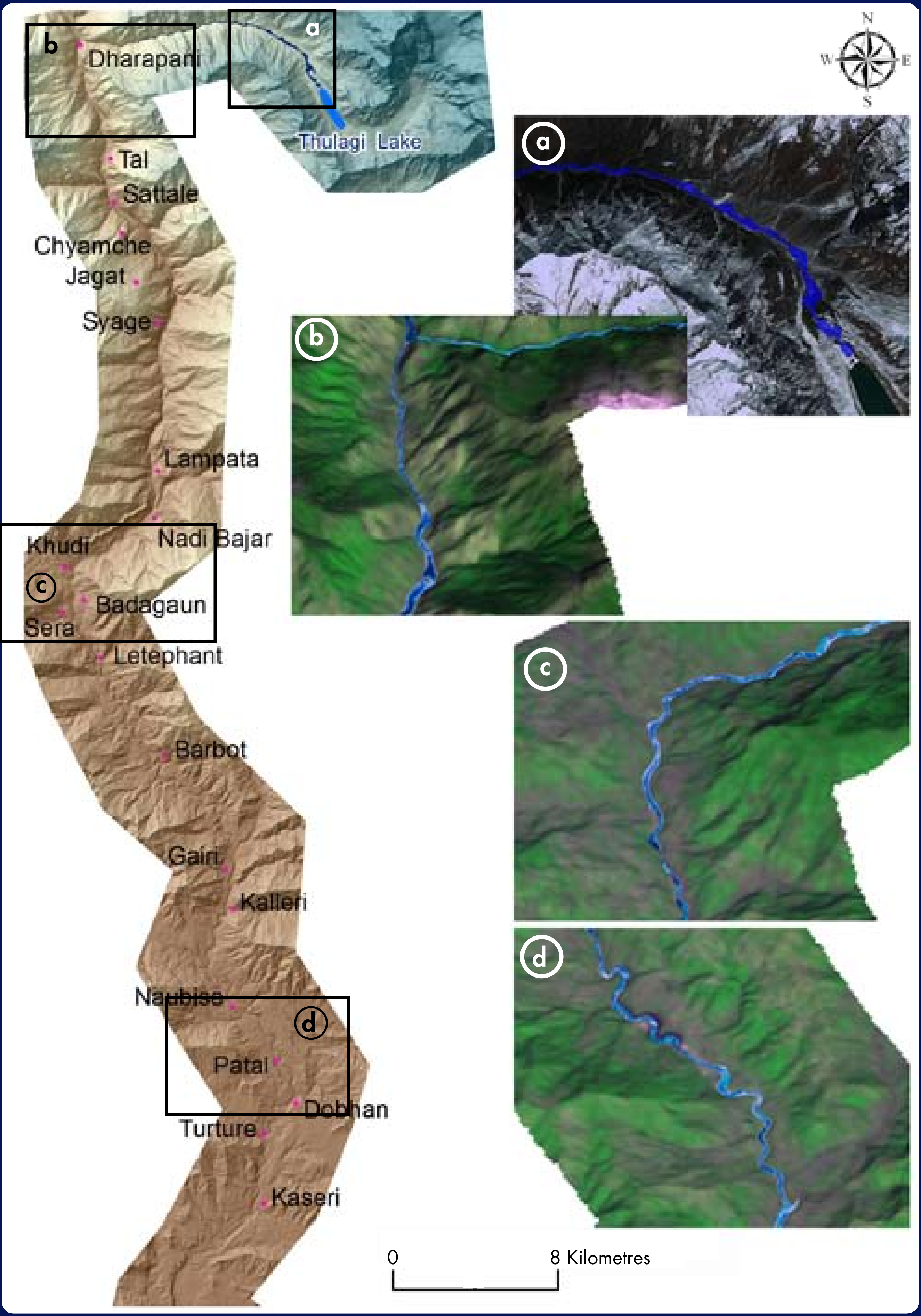
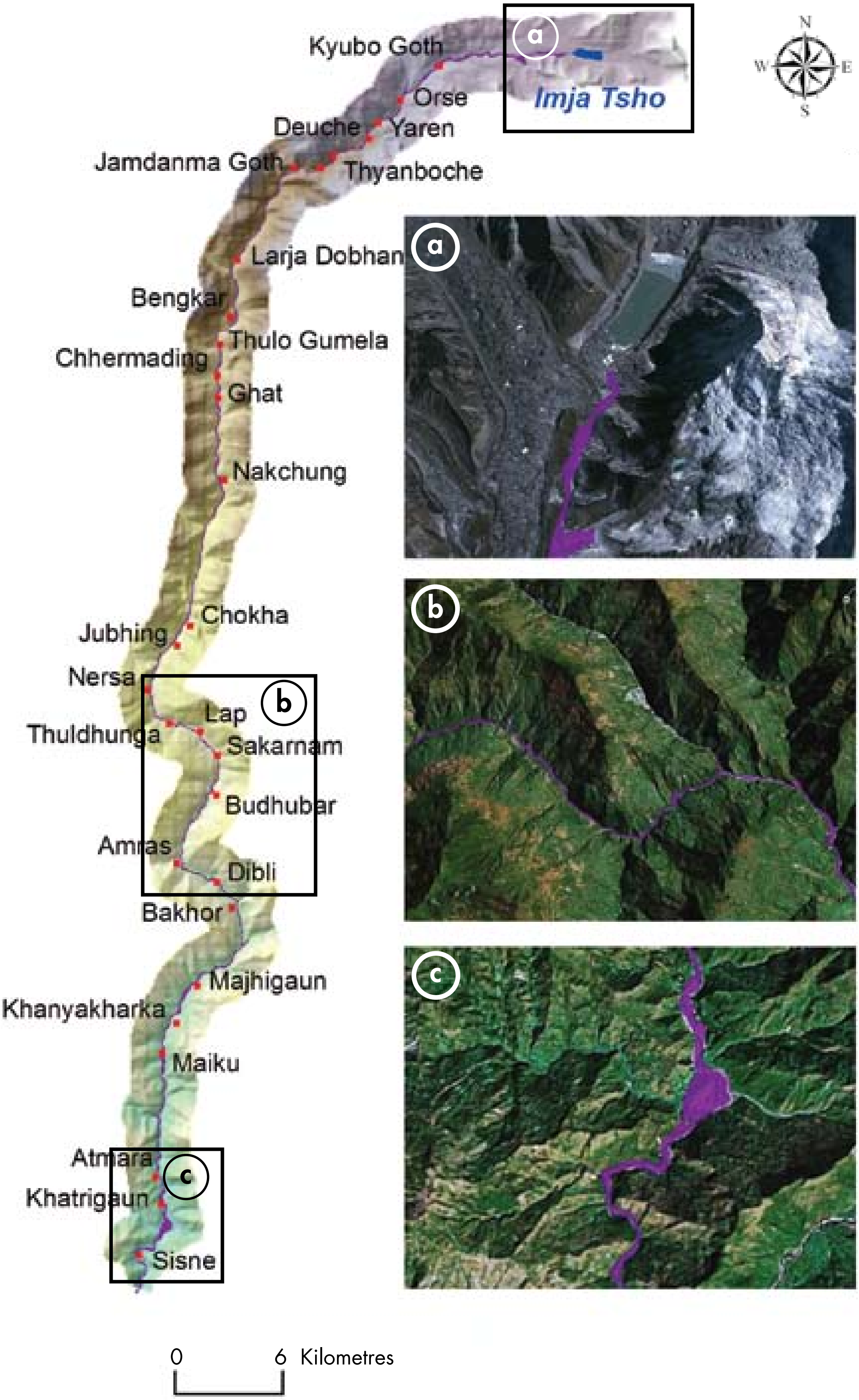


Figure 8.7: **Modelled flood inundation map along Dudh Koshi valley downstream of Imja Tsho**



Rolwaling river downstream of Tsho Rolpa from the end moraine showing the old (right) and new (left) outlet channels, 3 August 2009

9 Vulnerability Assessment

Introduction

To assess, and then mitigate, GLOF risks, it is essential first to estimate the actual potential for damage. This entails understanding both the hazard magnitude and the physical and socioeconomic vulnerability downstream. Determining the probability and magnitude of an event and assessing vulnerability and risk, are necessary for the preparation of response strategies. The probability of loss and /or damage can only be substantially reduced and resilience and /or restoration enhanced after a proper assessment of probable flood magnitude and impact. This chapter deals with vulnerability assessment.

There are two effects related to a GLOF hazard, a primary one characterised by inundation, erosion, and sedimentation up to the maximum calculated flood level, and a secondary one of slope failure that extends beyond the flood level depending upon the geology and materials in the river bed and its surroundings. Failures from past GLOFs were reported to extend up to 35 m above the river bed in areas where slopes were steep and unstable. Accordingly, the flood hazard zone is in two distinct parts: the 'modelled flood level', derived from numerical analysis of the hydrological model (dam-break model), and the 'maximum affected level', covering the area along the river bank up to 35 m above the river bed.

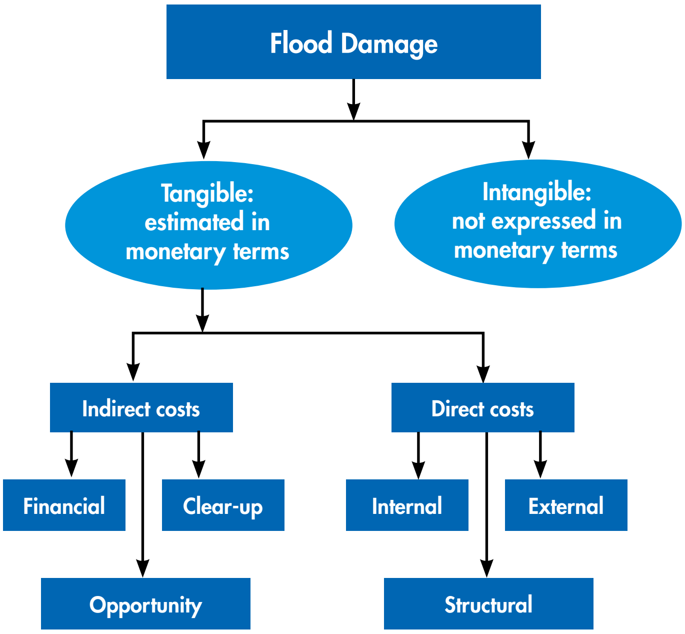
A vulnerability assessment was carried out for each of the three lakes and their downstream areas. The main objective was to obtain a systematic assessment based on past records, flood modelling, and interaction with local key stakeholders. The specific objective was to identify and quantify the elements exposed to risk, assess their vulnerability in terms of recovery and/or resilience, and identify and recommend strategies to increase the capacities of local people and institutions.

Economic Vulnerability

The economic elements exposed to GLOFs include lives, property, development projects and infrastructure, livelihood support systems such as tourism and trade, and environmental resources such as forest, pasture/ grazing land, and fisheries. The capacity of local people to cope with a natural disaster depends largely upon the diversity and quantity of household assets and access to information, technology, service infrastructure, and institutions; and this includes the degree of local participation.

We have defined damage in monetary terms based on the sum necessary to restore an area to its status quo ante. The damage caused by a GLOF event can be extensive and includes impacts on individuals and the community (Figure 9.1). Damage to property is the most common; the severity depends on three variables: the duration of the flood, the velocity of the flow, and the flooding level. Human lives can also be lost. Overall, the flood can cause varying degrees of distress and hardship.

Figure 9.1: **Types of flood damage**



Source: Guidance on the Assessment of Tangible Flood Damages, September 2002, Brisbane: The State of Queensland, Department of Natural Resources and Mines

Tangible damage can be estimated easily in monetary terms and can be grouped into direct and indirect damage. All physical assets affected are included in tangible damage. Direct damage (internal, external, and structural) usually accounts for most of the damage incurred. Indirect damage results from direct damage. For example, the breakdown of a section of a highway will either halt traffic or cause it to be diverted. The associated cost of this alternative is treated as indirect damage. Other examples of indirect damage could be closure of businesses or revenue or salary losses incurred from a breakdown in supplies, or costs incurred in ensuring people's health and wellbeing; in addition to which there will be the cost of repairing the direct damage.

Intangible damage refers to the negative impacts on social life which will extend well beyond the immediacy of the event. Important heritage sites can be lost and environmental quality (e.g., water quality) may deteriorate. Intangible damage reflects the social costs inflicted by an event which are not quantifiable, and refer to insecurity, distress, and depression, or inconvenience. Assessing intangible damage in monetary values is often not possible.

Hence only the tangible damage that can be expressed in monetary units was calculated when assessing the potential economic impact of a GLOF. The parameters used include the current purchase value of household assets – land, crops, livestock, and so on – and the cost of replacing infrastructure. In the case of roads and hydropower plants, the national average per unit cost is used; and the estimate is for the infrastructure as a whole as partial values are not easily derived, for example for hydropower projects. Secondary damage, such as the disruption of goods and services because of damage to infrastructure, is taken into consideration, but losses in tourism were not taken into consideration in this study because they are difficult to assess. However, an attempt was made to discuss potential GLOF risk to trade and tourism qualitatively during group discussions with the people who live in the basin.

Social Vulnerability

Social vulnerability assessments were derived from demographic and social characteristics such as the number of households, the population, and caste and/or ethnicity. The local capacity for GLOF risk management was assessed through household income (poverty) and livelihood support systems (sources of income, landholding size, and food sufficiency); literacy/education; skills; preparedness plans and practices such as land-use codes and standards; and social relations, institutions, and networking.

Methodology and Limitations

Primary and secondary sources of data were used for the study. Published and unpublished documents were collected and reviewed for secondary data. Primary data were collected in the field using a structured checklist. A key informant survey was held as well as group discussions. Transect walks and direct observation from the lakes and downstream areas were made. The information was entered onto topographic maps and recorded in field notes. Interviews took place in 12 areas around Thulagi Lake, 16 around Tsho Rolpa, and 23 in the Imja Tsho basin. Discussion group sizes ranged from 7 to 12.

The same methodology was adopted for all three lakes. Two different scenarios were used to identify GLOF-prone areas: one based on the flood level derived from the dam-break and hydrodynamic model, and the other based on a maximum height of 35 m from the river bed based on the maximum flood heights of past GLOF events. This height was used for development of a worst case scenario. Past events were considered when estimating the flood surge and extent of downstream damage, including the Nare GLOF in the Dudh Koshi valley in 1977; and the Zhangzangbo GLOF along the Bhote Koshi-Sun Koshi in 1981. Based on these events, the study carried out vulnerability and risk assessments for up to 100km downstream from the glacial lakes.

There were limitations in terms of identifying and qualifying elements at risk as well as socioeconomic and locational vulnerability. There was no detailed information available about existing infrastructure, such as the strength of the foundations or stress resistance, and hence physical vulnerability could not be assessed. The study had to rely heavily on information provided by the local people. There was also no record of internal damage as the field studies did not include detailed household surveys.

Estimated Exposure to Potential GLOF Risk

People and settlements

The downstream population in the adjoining village development committee (VDC) areas ranges from 96,767 for Imja, to 141,911 for Tsho Rolpa, and 165,068 for the Thulagi area. Of these, at the household level, the number of people likely to be affected by a potential GLOF varied from 953 in the modelled scenario to 3,808 in maximum scenario for Thulagi Lake; from 1,985 to 5,183 for Tsho Rolpa and from 5,784 to 7,762 for Imja Tsho. The remaining population could suffer a loss of environmental resources and service infrastructure. The maximum number who could be indirectly affected through infrastructural damage and loss of goods and services ranges from 501,773 for Imja, to 524,323 for Tsho Rolpa, and 2,044,145 for Thulagi (Table 9.1).

Table 9.1: **Population downstream within 100 km that could be affected**

Description	Imja Tsho	Tsho Rolpa	Thulagi
Population potentially directly affected due to loss of resources	96,767	141,911	165,068
Population potentially indirectly affected	501,773	524,323	2,044,145
Revenue earned in billion US$	8.98	2.4	2.2

Table 9.2 summarises the number of households and population likely to be directly affected and types and quantity of private property exposed to a potential GLOF. Information from the 1981 GLOF along the Bhote Koshi-Sun Koshi is also presented for comparison.

Table 9.2: **Summary of lives and property exposed to a potential GLOF risk**

Flood Scenario	Imja Tsho		Tsho Rolpa		Thulagi Lake		Bhote Koshi-Sun Koshi	
	Modelled flood	Maximum	Modelled flood	Maximum	Modelled flood	Maximum	GLOF in 1981	Maximum
Households								
No of households living inside flood-prone area	360	710	142	331	132	298	731	2,100
No of households having property inside flood-prone area	715	801	280	835	41	339	135	419
Total	**1,075**	**1,511**	**422**	**1,166**	**173**	**637**	**866**	**2,519**
Population								
No of people living inside flood-prone area	1,928	3,481	680	1,604	700	1,690	4,937	13,873
No of people having property inside flood-prone area	3,856	4,281	1,305	3,579	253	2,118	845	2,440
Total	**5,784**	**7,762**	**1,985**	**5,183**	**953**	**3,808**	**5,782**	**16,313**
Houses								
No of 'pakki' houses	59	238	85	200	77	195	248	586
No of 'kachchi' houses	386	570	60	130	48	103	483	1,527
Total	**445**	**808**	**145**	**330**	**125**	**298**	**731**	**2,113**
Land								
Area of khet land (ropani)	5,340	5,420	478	2,227	219	1,371	556	2,006
Area of bari land (ropani)	835	2,002	48	314	421	774	155	1,265
Total	**6,175**	**7,422**	**526**	**2,541**	**640**	**2,145**	**711**	**3,271**

Note: pakki = permanent, kachchi = temporary, khet = irrigated land, bari = rainfed land, ropani = unit of area (1 ropani = 0.0509 ha)

Exposure of property and infrastructure

GLOF events have downstream impacts at four different levels: individual household, VDC, district, and national. At the household level, impacts are either direct (from inundation) or secondary (e.g., from erosion or landslides). At the VDC level, people are affected by a loss of natural resources and service infrastructure. At the district level, damage to physical infrastructure disrupts the flow of goods and services, and at national level power supplies are disrupted because of damage to hydroelectricity projects, affecting populations living far beyond the GLOF area. The potential GLOF risk levels in the three glacial lakes studied were compared with the calculated GLOF impact on the Bhote Koshi Sun Koshi. The potential impacts were relatively higher for Imja than for Tsho Rolpa and Thulagi, and comparable to those of the Sun Koshi. This is because the Imja Tsho area lies within one of the top 10 tourist destinations in Nepal, whereas Tsho Rolpa (Rolwaling Conservation Area) and Thulagi (Annapurna Circuit) receive fewer tourists.

Monetary Value of the Elements Exposed

Table 9.3 summarises the monetary value of the elements exposed to a potential GLOF, and thus the potential cost of the damage, based on the modelling exercises. Again, the values from the Bhote Koshi-Sun Koshi GLOF are included for comparison. The revenue referred to is mainly from hydroelectricity.

Table 9.3: **Summary of monetary value of elements exposed to a potential GLOF risk (USD '000)**

Glacial lakes	Imja Tsho		Tsho Rolpa		Thulagi		Bhote Koshi-Sun Koshi	
Flood scenario	Modelled flood	Maximum	Modelled flood	Maximum	Modelled flood	Maximum	GLOF in 1981	1981 level+10m
Real estate	8,917	31,729	1,411	6,524	2,036	6685	15,889	40,606
Agricultural sector	932	1,680	117	330	234	519	246	996
Public infrastructure	2,037	2,084	319	1,928	335,784	339,469	98,845	109,446
Revenue	7	7	0	0	68,678	68,678	37,762	37,762
Total	**11,894**	**35,501**	**1,847**	**8,781**	**406,731**	**415,351**	**152,741**	**188,810**

The monetary value of elements exposed to a potential GLOF is quite high in the lower downstream areas in all three basins studied. This area accounts for 99% of the total amount for Tsho Rolpa and Thulagi and 51% for Imja Tsho according to the flood model. This can be explained by the increased amount of infrastructure downstream. An increase in GLOF level, however, would lead to increased damage in the headwater region.

Several proposals for hydroelectricity projects for the Marsyangdi river have been submitted to the Government of Nepal and they are likely to be commissioned in the near future. Should these projects be implemented, the risks to power supplies and revenue will be substantial: a total of USD 8.98 billion for the Imja Tsho, 2.4 billion for Tsho Rolpa, and 2.2 billion for Thulagi unless risks can be mitigated.

The flow of people and goods along routes to tourist destinations in the Dudh Koshi (Imja), Marsyangdi (Thulagi), and Rolwaling and Tama Koshi (Tsho Rolpa) varies considerably: more than 30,000 tourists visit the Dudh Koshi in the Khumbu region annually and 16,000 tourists visit the Dharapani area (near Thulagi). The number visiting the Tsho Rolpa area is unknown. The roads built for the Upper Tama Koshi hydroelectricity project in the Tama Koshi (Tsho Rolpa) and for the Manang area (Thulagi) have not only increased economic activities but also GLOF risks. Tourist facilities have been established along the river banks in high risk areas and, hence, the potential danger has grown.

The human capacity to deal with a GLOF event is poor. Farms are not large enough to provide sufficient food, and incomes are low. Indigenous ethnic groups account for more than 83% of the total families in the Imja Tsho area, 69% in the Tsho Rolpa area, and 90% in the Thulagi area. The Majhi and Thami, the main indigenous ethnic groups in the Tsho Rolpa area, are among the poorest people in Nepal and do not have the means to withstand and overcome a catastrophic natural disaster such as a GLOF. There are, of course, many other groups (including Tamang, Gurung, Rai, Magar, Sherpa, and Newar), but mountain groups as a whole are disadvantaged in Nepal with less access to education, resources, and national decision-making processes.

The exposures to the potential GLOF needed for the risk computation were calculated on the basis of information from focus group discussions, questionnaires, and transect surveys using replacement costs. These are preliminary estimates based upon existing infrastructure and not the potential economic benefit that could be harnessed in the future. The proposed large hydropower projects in the Tama Koshi basin would change the GLOF vulnerability of Tsho Rolpa in comparison to the other two areas. Thus estimations of vulnerability may change considerably over a short span of time depending upon the development activities in different basins. Changes in socioeconomic parameters will also influence future assessments.

The vulnerability of people living downstream from the three lakes differs in relation to the livelihoods and infrastructure characteristics of each area. Overall, the risk may change with passage of time and may also increase in the context of current atmospheric warming. In national terms, other lakes must also be considered. It is essential to develop an appropriate strategy and policy as well as short- and long-term action plans for GLOF risk management. The findings of the current study serve as a resource guide and provide materials for assessing GLOF hazards, socioeconomic vulnerability, and GLOF impacts downstream in Nepal. It is hoped that the findings will be useful in designing GLOF risk management and reduction strategies in Nepal, as well as throughout the Himalayan region.

Section 3

Discussion, Recommendations and Conclusion

Monjo village downstream of Imja Tsho, 1 June 2009

10 Monitoring, Early Warning and Mitigation

Risk results from a combination of the actual hazard and the vulnerability of people and their environment (United Nations 2006). Thus a risk can be minimised by lowering the level of hazard as well as by reducing vulnerability. Mitigation is the word used to describe actions to reduce the hazard and risk level.

A detailed discussion of mitigation is beyond the scope of this publication. But some of the major points and actions taken in Nepal are summarised in the following to indicate the possibilities. Some mitigation measures in Nepal have been described in Ives et al (2010).

Mitigation measures can be structural and non-structural. Measures include monitoring to provide an early indication of changes, early warning systems (EWS) to provide downstream residents and owners of infrastructure time to take avoidance action, and mitigation measures to physically change the situation and reduce the hazard and risk.

Nepal has made considerable progress in GLOF risk knowledge, risk assessment, monitoring, and early warning as well as some progress in mitigation measures. Some glacial lakes in Nepal are being monitored; early warning systems have been developed and installed in the Tsho Rolpa and Tama Koshi valleys as well as in the Upper Bhote Koshi area. Structural mitigation activities for GLOF risk reduction were carried out for Tsho Rolpa, but such measures are very expensive and it is unlikely that this approach could be utilised in the case of all 21 glacial lakes in Nepal that have been identified as potentially posing a risk of a GLOF.

Monitoring

Monitoring GLOF hazard levels requires a multi-staged, interdisciplinary approach using multi-temporal data sets. Key indicators include changes in the lakes and their impoundments which should be observed using different data sets at varying time scales to evaluate glacier hazard and stability of moraine dams. A considerable amount of information can be derived using remote sensing approaches to identify changes in lake size, and flight observation with small format cameras to observe lakes more closely. Monitoring of critical lakes may require direct periodic observation. To be effective, this should be carried out in cooperation with all stakeholders: communities, government departments, institutions, agencies, and broadcasting media, and others.

An automated monitoring system has been set up for Imja Tsho in partnership with DNPWC in Nepal, AIT in Thailand, and Keio University in Japan as a test for developing an early warning system (see Ives et al. 2010).

Early Warning

Early warning is defined as: "The provision of timely and effective information, through identified institutions, that allows individuals exposed to a hazard to take action to avoid or reduce their risk and prepare for effective response" (United Nations 2006). For an early warning system to be effective, it must integrate four elements: knowledge of the risk, a monitoring and warning service, dissemination and communication, and response capability.

Early warning systems need to be technically sound, simple to operate, easy to maintain or replace, and reliable so that accurate and timely warning can be given. The human communication networks must be capable of relaying the warning to the appropriate authorities. Maximum effectiveness would most likely be achieved if the warning systems are placed in the hands of the local communities. The systems tested in Nepal have met with mixed success.

A manual early warning system was set up in the Tsho Rolpa area and downstream in 1997, when the army and police in the area were provided with communication sets, following considerable awareness raising activities. In 1998, a fully functional automatic system was put in place before mitigation work commenced on Tsho Rolpa (Reynolds 1999; Bajracharya et al. 2007). However, by 2002 the system was no longer operating, in part because local residents assumed that the lake had been lowered to a safe level. Damage also appeared to have incurred during the recent period of political unrest and as a result of new developments such as roads (Ives et al. 2010).

An early warning system was also installed in the upper Bhote Koshi valley near the Friendship Bridge on the Nepal-China border in eastern Nepal in 2001. This was intended to protect the Upper Bhote Koshi Hydroelectric Project. This system, however, has a lead time of only six minutes as the stations are all within the Nepal part of the catchment. To be really effective, sensors need to be installed in the Tibet Autonomous Region to cover the upper catchments. The system was still functioning in 2009, presumably because of the interest of the hydropower project (Ives et al. 2010).

Mitigation

There are several possible methods for mitigating the impact of GLOFs. The most important mitigation measure is to reduce the volume of water in the lake, thus reducing the magnitude of the possible peak discharge at the time of breach. Structural mitigation measures can also be applied downstream to protect infrastructure from peak floods.

The volume of water can be reduced by means of one or more of the following: controlled breaching of the moraine dam; construction of an outlet control structure; pumping or siphoning the water from the lake; and tunnelling through the moraine barrier or under an ice dam.

Preventative measures can also be carried out around the lake to secure against potential threats such as loose rocks or snow/ice avalanches that could trigger displacement waves.

Infrastructure downstream (diversion weirs, intakes, bridges, or river bank settlements) can be protected against a possible surge through proper construction that allows sufficient space for the flow of water and avoids damming. Bridges should have appropriate flow capacities at elevations higher than expected GLOF levels and the spans of piers should not be obstructed by uprooted tree trunks. Land use zoning should also be considered as an effective approach to mitigation by reducing the structures and elements at risk. Among others, settlements should not be built on or near low river terraces within the GLOF hazard zones. River banks with potential or old landslides and scree slopes near settlements should be stabilised and appropriate warning devices installed.

Tsho Rolpa is the only glacial lake in Nepal that has been subjected to mitigation measures. A siphon system installed in 1995 had only limited success. It was followed by cutting of an open channel through the moraine dam; the four metre deep artificial spillway completed in 2000 succeeded in lowering the lake level by three metres.

Awareness Raising

Besides monitoring lakes, it is essential to raise local awareness, and increase knowledge about how to respond. Community and local government bodies should focus on monitoring the lakes, mitigating their vulnerability to GLOF, and preparing to cope with such events should they occur: early warning begins with disaster preparedness. This involves raising awareness about glacial lakes, their characteristics, level of hazards, and the required responses during and after GLOF events.

11 Guidelines for GLOF Risk Management and Strategy in Nepal

Introduction

Glacial lakes in the Nepal Himalayas have been categorised and mapped systematically; nevertheless there are prevailing risks. Increased human pressure in high mountain areas in Nepal and growing socioeconomic vulnerability mean that GLOF risk management is needed.

Risk management in the broadest sense is defined as "the creation and evaluation of options for initiating or changing human activities or (natural and artificial) structures with the objectives of increasing the net benefit to human society and preventing harm to humans and what they value; and the implementation of chosen options and the monitoring of their effectiveness" (IRGC 2005).

In October 2009, a 'National Strategy for Disaster Risk Management' was approved by the Nepal Home Ministry. A qualitative change is visualised in this strategy document based on realisation of the need to mainstream disaster risk management into development activities and to shifting the emphasis from relief to preparedness. The document also proposes an organisational set up for a 'National Authority for Disaster Risk Management (NADRM)' under the Ministry of Home Affairs for implementation of disaster risk management plans. In addition, a 'Disaster Management Act 2009' was drafted and is in the process of promulgation.

The Government of Nepal adopted a 'National Action Plan on Disaster Management in Nepal' on 18 February 1996 in view of 1990-2000 being declared the 'International Decade of Natural Disaster Reduction' (IDNDR) by the United Nations General Assembly (Resolution 44/23622 December 1989). This has improved understanding and capacity in hazard assessment and mapping of recurring disasters and a component on disaster risk reduction has been included in national development plans. The Tenth Five Year Plan (2002-2007) and Three-Year Interim Plan (2007-2010) incorporated disaster risk reduction (DRR) and preparedness and mainstreaming of DRR components. Nepal has also ratified the Hyogo Framework for Action (HFA) 2005-2015, adopted at the UN World Conference on Disaster Reduction, Kobe, in 2005.

Other documents related to disaster preparedness and its policies in Nepal include the following:

- Natural Disaster Relief Act, 1982
- National Action Plan for Disaster Management in Nepal, 1996
- Tenth Five Year Plan (2002-2007)
- National Water Plan, 2005
- Water Induced Disaster Management Policy, 2006
- National Policy and Strategy for Disaster Risk Management, 2007
- National Strategy for Disaster Risk Management, 2009
- Disaster Management Act (draft)

Essential Components of GLOF Risk Management

The National Strategy for Disaster Risk Management (2009) refers to disasters in general: it includes GLOF risk but does not address it distinctively. National strategies and approaches to disaster risk management pay little attention to GLOF risk management, perhaps because information about it is inadequate. It is essential to develop short- and long-term action plans and programmes.

GLOF risk is difficult to predict and it is impossible to guarantee absolute safety, hence GLOF risk management is needed to minimise the loss of lives and property. For effective GLOF risk management, it is essential to define components and their relevant issues so that appropriate strategies can be established. The main components that need to be addressed are outlined in the following section.

Knowledge about risks

It is essential to know the GLOF risk in order to manage it properly. Thus continued assessment of GLOF hazard and vulnerability is an integral part of risk management; it requires the following:

a) Detection – mapping and classifying glacial lakes and ranking them using remote sensing and aerial photographs
b) Field visits to the potentially critical lakes to determine the GLOF hazard
c) Assessment of GLOF hazards in terms of magnitude and frequency, including mapping of GLOF hazard and flooding zones
d) Vulnerability assessment in the hazard zones; assessment of environmental and socioeconomic impact is essential for this
e) Risk mapping through an analysis of the possible interaction of a GLOF hazard and vulnerability

Monitoring risk

Effective monitoring is important for disaster preparedness and should involve use of remote sensing, aerial observations, and field study; it requires the following:

a) Regular repeated mapping of lakes using remote sensing and monitoring of key indicators of glacier and GLOF hazards
b) Regular investigation of the development of hazards and risk in a periodic manner including regular evaluation of the effectiveness of any mitigation measures implemented
c) Field-based monitoring of GLOF hazard and risk in critical lakes in the field
d) Regular monitoring of seepages, ice cores, and slope instability in the end moraine complex and of the stability of the natural moraine dam
e) Regular monitoring of exceptional input of drainage as discharge and debris from side valleys into the lake as well as discharge from the lake
f) Monitoring of lake storage volume, bottom of the lake, and shape
g) Regular monitoring of surroundings of lakes, e.g., hanging glaciers, for changes in snow mass, position, and slope instability to evaluate possibility of triggering

Preparedness

Preventative and precautionary measures are needed to minimise human and economic vulnerability. Prevention entails adapted use of space by trying to avoid hazards. Where this is not possible, structural, technical, or biological measures should be taken to minimise the intensity of the natural process (www.planat.ch, accessed 20 July 2010).

Early warning should provide information in time for response. The preparedness strategy should address as a minimum, but not only, the following:

a) Ensure that hazard maps are prepared of potentially dangerous lakes and their flow paths.
b) Land-use planning should determine development planning.
c) Structural mitigation measures should be undertaken to eliminate protection deficiencies.
d) Establishment of early warning systems is essential: one related to communicating changes in water level in the lake with community participation, and another in the form of a mechanical system with sirens.
e) Provisions must be made in legislation and policies so that infrastructure developers, especially private hydropower developers, are engaged in GLOF early warning and risk reduction activities.
f) GLOF risk reduction should be considered as a national as well as a local priority.

Community participation in risk reduction

Dissemination and communication of GLOF risk information and early warnings to individuals and communities threatened by hazards is an essential part of risk management. Decentralisation of risk management activities to communities and local authorities will encourage their ownership and participation at all levels. The following actions are necessary to ensure community involvement:

a) Communicate and disseminate at least the key findings of GLOF hazard and vulnerability mapping and risk assessment to key stakeholders at different levels – the community, VDC, DDC, and nationally.
b) Awareness creation programmes should be developed and implemented.
c) Community leaders should be trained on what to do, how to do, where to do, and when to do before, during, and after GLOF disasters. Training manuals should be prepared accordingly.
d) Put communities in charge of early warning systems so that they are properly maintained.

Transboundary dimensions

Impacts of GLOF are not limited within the borders of a country. In the past, many GLOF events that originated in the Tibet Autonomous Region of China caused heavy damage in the territory of Nepal. Hence, it is necessary to address transboundary dimensions of GLOF.

a) It is essential to ensure that the regional and international collaboration for GLOF risk mitigations deals with cross-border problems.
b) Mechanisms for inter-governmental collaboration in sharing data and information are essential: different levels of collaboration should be explored.

Institutional arrangements

Organisational arrangements should be made for appropriate GLOF risk management clarifying the roles of the key government agencies involved. A National GLOF Risk Reduction Fund should be established for research, awareness creation, design, implementation, and monitoring of mitigation and adaptation measures. For this, the following are necessary:

a) An institutional basis should be established to implement GLOF risk reduction activities.
b) Research to improve hazard management and capacity building should be promoted.

Issues and Activities of GLOF Risk Management

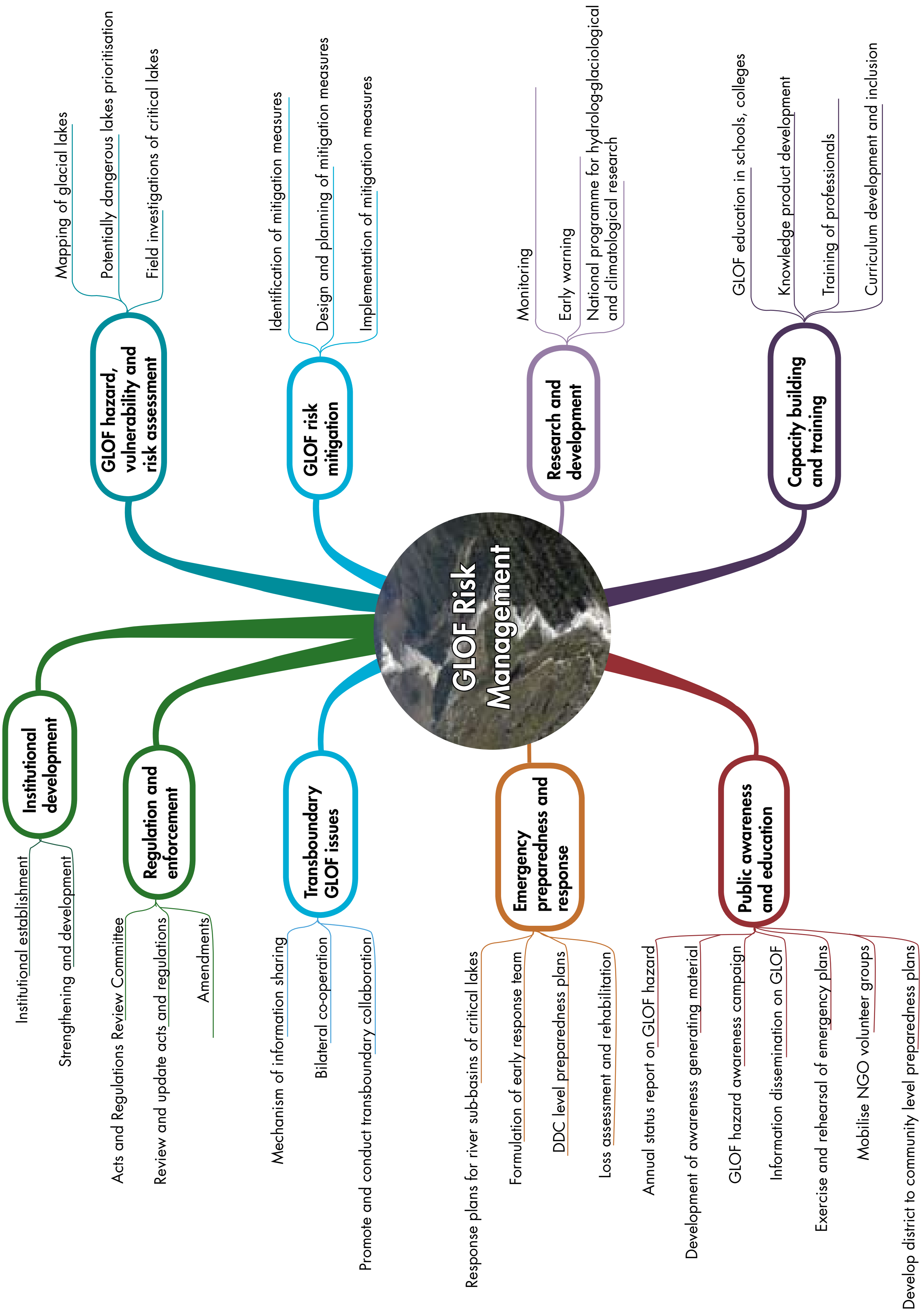
Issues ranging from knowledge of risks to institutional arrangements are required as a guideline for strategy development, including the following:

1. GLOF hazard, vulnerability, and risk assessment
2. GLOF risk mitigation
3. Research and development
4. Capacity building and training
5. Public awareness and education
6. Emergency preparedness and response
7. Transboundary GLOF issues
8. Regulation and enforcement
9. Institutional development

The systematic and coordinated activities related to these issues are illustrated in Figure 11.1. It is envisaged that the activities related to the components and issues will serve as guidelines for GLOF risk management strategies. Risk management is a continuous process and periodic evaluation of the dynamic processes of glacial lake formation and their expansion has to be monitored continuously. With the institutional development, the activities suggested here should be carried out in a five- or ten-year cycle and should include updating the inventory or mapping of lakes.

In developing the strategy for GLOF risk management, the components and issues mentioned above should not be dealt with in segregation. It is essential to note that these components are inter-linked and should be addressed with an integrated

Figure 11.1: **Issues and activities in GLOF risk management**



approach. The process must be developed such that there will be a feedback mechanism from one component to another. The integrated approach is illustrated with the help of a diagram (Figure 11.2) showing interlinkages and feedback mechanisms between and among all the components.

The GLOF Risk Management Plan should be embedded in the National Disaster Management Plan in accordance with the various disaster-specific guidelines laid down by the Ministry of Home Affairs/Government of Nepal and should incorporate the disaster management plans prepared by the central ministries and /or departments and district authorities for other disasters.

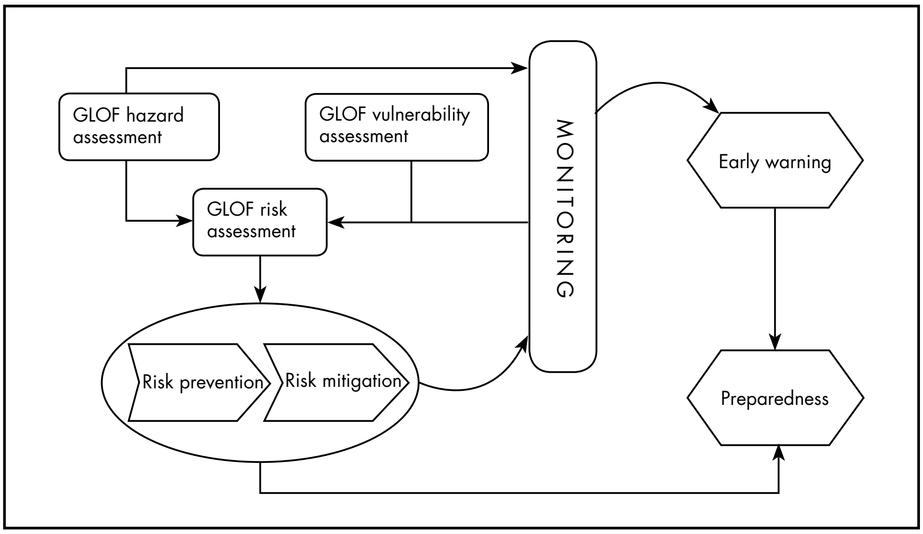


Figure 11.2: **Interlinkages and feedback processes between and among the components of GLOF risk management**
(modified after Stanganelli 2008)

Dona river downstream of Thulagi Lake at the junction with Marsyangdi river, 25 July 2009

12 Conclusions and Recommendations

The GLOF Risk in Nepal

The results in this report illustrate that, given the present state of knowledge, it is not possible to predict even approximate dates of occurrence or magnitude of risk posed by glacial lakes in Nepal. This represents the primary conclusion and leads to the quandary – how to respond to what is certainly a significant hazard? Serious loss of life and property has occurred in the recent past and the potential for future losses is high once a long-term view is assumed. At best, careful monitoring of existing glacial lakes and periodic search for the formation of new ones is essential. Stated without qualification, such a task would be overwhelming. Thus the report's findings, especially the methods employed to classify the existing lakes in terms of degree of perceived threat, is recommended as the most logical approach.

The study took a step-wise approach to ensure that coverage was as comprehensive as possible. At the same time careful deployment of the limited available manpower and financial resources constrained research, especially in the field, to be focused on a small number of the most critical lakes. These were identified during the first stages of the step-wise approach as illustrated in the foregoing chapters. Thus three of the largest existing lakes, Imja Tsho, Tsho Rolpa, and Thulagi Lake, were selected for intensive study. It is also important to emphasise that the three were all originally identified as critically dangerous. The current investigations, together with a survey of the more recent literature, have led to the conclusion that the earlier fears of imminent catastrophe were much exaggerated. This in itself is an important conclusion.

Although the three lakes have been evaluated as relatively stable, the possibility for a GLOF to occur sometime in the future cannot be dismissed. More than a dozen significant GLOF events have occurred since 1980 that resulted in serious loss of life and property. It seems likely that such events will occur again, particularly in view of continued atmospheric warming and the associated increase in volume of glacial lakes. Furthermore, expansion of infrastructure in the vulnerable sectors downstream means that the actual risk associated with an individual event is increasing. As with earthquakes, the difficulty lies not in predicting that such an event is likely to take place, rather the problem is that in the current situation it is impossible with any certainty to predict where such an event will occur, and whether this year, next year, or in the remote future. However, because such an event could be imminent, it is vital that steps be taken to mitigate against severe loss of life and property.

Chain reactions and the problem of small lakes

There is a further problem associated with the criteria used to select potentially critical lakes. Very small lakes were excluded from the study as posing little risk, with a recommendation to repeat the inventory at fixed-time intervals (e.g. 5-10 yrs). The recommendations of the Glacier and Permafrost Hazards in Mountains (GAPHAZ) Working Group emphasise that chain reactions and interactions must also be considered when assessing hazards and risk associated with glaciers and permafrost in mountains (GAPHAZ 2007). This applies as much to glacial lakes as to other hazards. The GLOF hazard assessments need to take into account possible interaction of processes or chain reactions as the implications can be complicated and far reaching. One of the many chain reactions that could take place in the Himalayas is that the outburst of a comparably small lake that is situated above another lake or lakes causes a flood and exceptionally large inflow into the other lake or series of lakes, which subsequently burst out. The total discharge of such a chain could be much larger than anticipated from analysing individual lakes only. The triggering lake could even be an erosion lake, considered secure, but squeezed out by an avalanche. This is one of the reasons why smaller lakes can actually pose a large hazard.

One example of this type of lake that has been identified is the Kabung Tshoding lake. The lake is situated about 500 m above the left lateral moraine of Tsho Rolpa. After traversing very long and steep mountain slopes, it drains into the left side valley of Tsho Rolpa. However, the lake does not have large masses of hanging glaciers that might lead to a surge that would overtop the moraine dam.

The Three Lakes in the Study

Each of the three lakes subjected to detailed study formed from the amalgamation of small melt-ponds on the lower sections of the glacier surfaces. Over the last 50 to 60 years, these expanded into large pro-glacial lakes more than a kilometre in length and up to 100 metres deep; some of the original glacier ice may still be present beneath the lakes. Thus immense volumes of water have accumulated. They present a difficult problem: they could cause significant damage should they burst; but they also offer a valuable form of water storage should they be managed appropriately. Of the three, Tsho Rolpa, despite being lowered artificially, is probably the most unstable as a result of its 216 m high and narrow end-moraine dam. However, the overall indication is that none of the three lakes is at immediate risk of bursting out.

All three lakes drain through their end-moraine dams along relatively stable channels, but all three are continuing to expand upstream into the retreating termini of their glaciers. The lake expansion itself is a major factor in the rapid retreat of the three glaciers, in addition to the direct impact of atmospheric warming. The potential for catastrophic outburst of these lakes depends on the stability of the end-moraine dams, and the effect of the slow melting of buried ice and permafrost within them. Seismic activity might also affect dam stability, but such activity is even more difficult to predict, and was not taken into account in this study.

Example of a chain reaction – Thorthormi and Raphstreng lakes in Bhutan

One of the striking examples in the Himalayas of a chain reaction posing a GLOF hazard is that of the Thorthormi and Raphstreng lakes located in the headwaters of the Lunana area in the Bhutan Himalayas. These lakes were studied in detail by Bhutan's Department of Geology and Mines (DGM) after it was realised that a GLOF resulting from the combination of Raphstreng Tsho and Thorthormi Tsho, which are situated adjacent to each other, would result in the release of 53 million cubic metres of water (Karma et al. 2008). The Raphstreng Tsho and Thorthormi Tsho are interconnected by a 30 m terminal moraine dam, with the Raphstreng Tsho lying 65 m below Thorthormi. Leber et al. (2002) warned that a GLOF resulting from a combined Thorthormi-Raphstreng outburst must be considered as a worst-case scenario. Furthermore, since the Raphstreng Tsho is closely located to the Lugge Tsho, the path of the likely Raphstreng Tsho flood outburst would be similar to the 1994 Lugge Tsho flood outburst.

In contrast to the three cases chosen for intense field investigation, all the recently recorded GLOFs in the Nepal Himalayas have issued from simple moraine-dammed lakes that accumulated behind end moraines of retreating 'clean-ice' glaciers. In each case, release was triggered by a surge wave caused by an ice/rock avalanche hitting the lake surface. The best-documented of these is the 1985 release of Dig Tsho, western Khumbu that destroyed the nearly complete Namche Small Hydel project (see chapter 2 above).

All three of the lakes studied have become tourist destinations. In addition, the access to Imja Tsho involves long stretches of the world-famous trekking route to Mt Everest (Sagarmatha) base camp. Thus, the possible occurrence of a major discharge from Imja Tsho during the trekking season could add several hundred lives to any accounting of the vulnerability of local people and infrastructure.

Awareness Raising

The local community needs to become more aware of GLOF hazards and ways and means to respond to warnings. It is important to continue dissemination of accurate information to the public, and raising of public awareness on glacial lakes and GLOF risk management, through a variety of means such as press reports, TV programmes, radio programmes, news articles, and scientific forums for public awareness.

Materials and knowledge products need to be developed to support awareness generation for different target groups, including school children – for example video films, brochures in local languages, and CD- ROMs. Exercises and rehearsal of emergency plan and programmes on escape, relief, and rescue from GLOF events can also help to raise public awareness.

During the surveys, close contact was maintained with the local people as a first approach to promoting awareness and encouraging future collaboration. The preliminary results of the surveys were discussed with the local communities in public events at each of the three sites, and summary leaflets prepared in Nepali were distributed.

Need for a National Policy

In view of the very high, if unpredictable, hazard involved, it is imperative that a national policy be developed for increasing awareness, early warning, and risk mitigation. This could then be used as a template for application to the entire Hindu Kush-Himalayan region. Furthermore, immediate action is urged along the following lines: increase of public awareness; more extensive vulnerability assessment; routine airborne and satellite monitoring; and more intensive and repeat geophysical survey. There also remains the inherent danger of trans-international border damage that requires international cooperation.

Region-wide cooperation throughout the Hindu Kush-Himalayas should follow, and it is recommended that steps be taken to organise a region-wide planning session for experts and leaders of relevant national institutions to develop a more coordinated approach and begin laying the foundations for a glacial lake outburst risk reduction policy.

Finally, despite the very high, although indeterminate, risks involved, the current tendency for grossly exaggerated reporting, in terms of both the imminence of possible catastrophe and its magnitude, should be severely discouraged.

References

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

Bajracharya, SR; Mool, PK; (2005) 'Growth of hazardous glacial lakes in Nepal.' In Yoshida, M; Upreti, BN; Bhattarai, TN; Dhakal, S (eds) *Proceedings of the JICA Regional Seminar on Natural Disaster Mitigation and Issues on Technology Transfer in South and Southeast Asia,* 30 September – 13 October 2004, pp131-148. Kathmandu: Tribhuvan University, Tri-Chandra Campus, Department of Geology with Japan International Cooperation Agency

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

Bajracharya, SR; Mool, PK; Shrestha, BR (2008) 'Global climate change and melting of Himalayan glaciers.' In Ranade, PS (ed) *Melting glaciers and rising sea levels: Impacts and implications*, pp28-46. Hyderabad: Icfai University Press

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

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

Bajracharya, SR; Maharjan, SB; Shrestha, BR (2010) 'Second generation glaciers mapping and inventory of Nepal.' *Journal of Nepal Geological Society* 41 (abstract volume special issue): 21

Bajracharya, SR; Maharjan, SB (2010) *The status of glaciers in the Nepal Himalaya*. Unpublished report prepared by ICIMOD, Kathmandu

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

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

Björnsson, H (2009b) *Jöklar á Íslandi*. Reykjavik (Iceland): Opna

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

BPC Hydroconsult (1998) *Tsho Rolpa glacial lake – How to save lives from the flood.* Lalitpur (Nepal): Butwal Power Company Hydroconsult

Budhathoki, KP; Dongol, BK; Devkota, LP; Dhital, NP; Joshi, SR; Maskey, PR (1996) *Aerospace survey and GIS for GLOF hazard zonation, Rolwaling and Tama Koshi valleys, Dolakha District, Nepal*. In postgraduate diploma course field work report on Mountain Hazard Zonation in the Himalayas with emphasis on GLOF, prepared for ITC, The Netherlands

Buchroither, MF; Jentsch, G; Wanivenhaus, B (1982) 'Monitoring of recent geological events in the Khumbu area (Himalaya, Nepal) by digital processing of Landsat MSS data.*' Rock Mechanics* 15: 181-197

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

Chikita, K; Yamada, T; Sakai, A; Ghimire, RP (1997) 'Hydrodynamic effects on the basin expansion of Tsho Rolpa glacier lake in the Nepal Himalaya.' *Bulletin of Glacier Research* 15: 59-69

Damen, M (1992) *Study on the potential outburst flooding of Tsho Rolpa Glacier Lake, Rolwaling Valley, East Nepal*. Enschede (Netherlands): Netherlands-Nepal Friendship Association, International Institute for Aerospace Survey and Earth Sciences, ITC

DHM (1997) *Thulagi Glacier Lake study*. Final report prepared for the Department of Hydrology and Meteorology, HMG/N, Kathmandu, Nepal, in cooperation with Federal Institute for Geo-sciences and Natural Resources (BGR), Hannover, Germany

DHM (2001a) *Preliminary analysis for the preparation of proposal for minimisation of potential glacier lake outburst flood hazard from Imja Glacier Lake*. Final report prepared by HAF Consultancy Service for the Department of Hydrology and Meteorology, Kathmandu, Nepal

DHM (2001b) *Topographical/profile survey and establishment of benchmarks of the end moraine of Imja Glacier Lake*. Final report prepared by Dip Consultancy for the Department of Hydrology and Meteorology, Kathmandu, Nepal

DHM (2002a) *The preparation of the digital database of Tsho Rolpa Glacier Lake, Part I, Time Series Data*. Final report, prepared by Shree Siradi Sai Baba Engineering Consultancy, July 2002, for the Department of Hydrology and Meteorology, Kathmandu, Nepal

DHM (2002b) *Digital database of Tsho Rolpa Glacier Lake, Part II, Spatial Data*. Final report prepared by HAF Consultancy Service for the Department of Hydrology and Meteorology, Kathmandu, Nepal

DHM (2003a) *Ground penetrating radar (GPR) survey, southern slump area of Tsho Rolpa Glacier Lake, additional services – Year 4*. Report prepared by BPC-Hydroconsult for the Department of Hydrology and Meteorology, Kathmandu, Nepal

DHM (2003b) *Ground penetrating radar (geophysical) survey of Tsho Rolpa Glacier Lake*. Draft completion report prepared by Deimos Engineering Consultancy (DECON) for the Department of Hydrology and Meteorology, Kathmandu, Nepal

DHM (2004) *Routine investigation of the key areas of Tsho Rolpa Glacier Lake*. Final report prepared by Society of Hydrologists and Meteorologists – Nepal (SOHAM-Nepal) for the Department of Hydrology and Meteorology, Kathmandu, Nepal

DNRM (2002) *Guidance on the assessment of tangible flood damages*. Brisbane: State of Queensland, Department of Natural Resources and Mines

Dwivedi, SK; Acharya, MD; Joshi, SP (1999) 'Tam Pokhari GLOF of 3rd September 1998, preliminary report.' *WECS Bulletin* 10(1):11-13

Fort, M; Freytet, P (1983) 'The quaternary sedimentary evolution of the intra-montane basin of Pokhara in relation to the Himalaya Midlands and their hinterland (West Central Nepal).' In Sinha, AK (ed) *Contemporary geoscientific researches in Himalaya,* Vol 2, pp91-96. Dehra Dun (India): Bishen Singh Mahendra Pal Singh

Fort, M (1987) 'Geomorphic and hazards mapping in the dry continental Himalaya: 1:50,000 maps of Mustang District, Nepal.' *Mountain Research and Development 7* (3): 222-238

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

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

GAPHAZ (2007) *GAPHAZ Recommendations, version 29.3.2007*. Recommendations prepared by the Glacier and Permafrost Hazards in Mountains (GAPHAZ) Scientific Working Group of the International Association of Cryospheric Sciences (IACS) and the International Permafrost Association (IPA). www.geo.uio.no/remotesensing/gaphaz/recomm.html (accessed 17 December 2010)

GEN; CREH; NU; DHM (2006) *Data Report 4 (2001-2004), GEN 2001-2002: Imja Glacier Lake in Khumbu, East Nepal*. Unpublished report prepared by Glaciological Expedition to Nepal, Cryosphere Research in the Himalaya, Department of Hydrospheric Atmospheric Science, Graduate School of Environmental Studies, Nagoya University, and Department of Hydrology and Meteorology, HMG of Nepal

Gyawali, D; Dixit A (1997) 'How distant is Nepali science from Nepali society? Lessons from the 1997 Tsho Rolpa GLOF panic.' *Water Nepal* 5(2): 5-43

Hambrey, MJ; Quincey, NF; Reynolds, JM; Richardson, SJ; Clemmens, S (2008) 'Sedimentological, geomorphological and dynamic context of debris-mantled glaciers, Mount Everest (Sagarmatha) region, Nepal.' *Quarterly Science Review* 27: 2361-238

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

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

Heuberger, H; Masch, L; Preuss, E; Schröcker, A (1984) 'Quaternary landslides and rock fusion in Central Nepal and in the Tyrolean Alps.' *Mountain Research and Development* 4(4): 345-362

Hewitt, K (1997) 'Risks and disasters in mountain lands.' In Messerli, B; Ives, JD (eds) *Mountains of the World: A global priority,* pp 371-408. London: Parthenon

Huggel, C; Haeberli, W; Kääb, A; Bieri, D; Richardson, S (2004) 'An assessment procedure for glacial hazards in the Swiss Alps.' *Canadian Geotechnical Journal* 41: 1068-1083

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

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

IRGC (2005) International Risk Governance Council, White Paper 1 on *Risk Governance: Towards an Integrative Approach*. Geneva: IRGC. www.irgc.org/IMG/pdf/IRGC_WP_No_1_Risk_Governance_reprinted_version_.pdf

Ives, JD (1986) *Glacial lake outburst floods and risk engineering in the Himalaya: A review of the Langmoche disaster, Khumbu Himal, 4 August 1985,* Occasional Paper No 5. Kathmandu: ICIMOD

Ives, JD; Shrestha, RB; Mool, PK (2010) *Formation of glacial lakes in the Hindu Kush-Himalayas and GLOF risk assessment*. Kathmandu: ICIMOD

JTC1 (2004) 'ISSMGE, ISRM and IAEG Joint Technical Committee on Landslides and Engineered Slopes (JTC1): ISSMGE TC32 - Technical Committee on Risk Assessment and Management *Glossary of risk assessment terms – Version 1*, July 2004. www.engmath.dal.ca/tc32/2004Glossary_Draft1.pdf (accessed 2 February 2011)

Kääb, A (2008) 'Remote sensing of permafrost-related problems and hazards.' *Permafrost and Periglacial Processes* 19: 107-136

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

Karma, T; Ghalley, KS; Thinley, U (2008) *Hazard zonation for glacier lake outburst flood along Punatshang Chu from Khuruthang to Lhamoyzinkha (ed Dorji Y).* Unpublished report prepared for the DGM – NCAP Project, Thimphu, Bhutan

Kettelmann, R; Watanabe, T (1998) 'Approaches to reducing the hazard of an outburst flood of Imja Glacier Lake, Khumbu Himal.' In Chalise, SR; Khanal, NR (eds) *Proceedings of the International Conference on Ecohydrology of High Mountain Areas,* Kathmandu, Nepal, 24-28 March 1996, pp 359-366. Kathmandu: ICIMOD

Lamsal, D; Sawagaki, T; Watanabe, T (2011) 'Digital terrain modelling using Corona and ALOS PRISM Data to investigate the distal part of Imja Glacier, Khumbu Himal, Nepal'. *Journal of Mountain Science*, 8 (3) In press

Leber, D; Hausler, H; Brauner, M; Wangda, D (2002) *Glacial lake outburst flood (GLOF) mitigation project: Pho Chhu Eastern branch (Thanza-Lhedi; 2002-2003).* Unpublished report prepared for University of Vienna, Vienna, Austria, and Geological Survey of Bhutan Thimphu, Bhutan

Lliboutry, L (1977) 'Glaciological problems set by the control of dangerous lakes in Cordillera Blanca, Peru. II. Movement of a covered glacier embedded within a rock glacier.' *Journal of Glaciology* 18 (79): 255-274

Lliboutry, L; Arnao, BM; Pautre, A; Schneider, B (1977a) 'Glaciological problems set by the control of dangerous lakes in Cordillera Blanca, Peru. I. Historical failures of morainic dams, their causes and prevention.' *Journal of Glaciology* 18(79): 239-254

Lliboutry, L; Arnao, BM; Schneider, B (1977b) 'Glaciological problems set by the control of dangerous lakes in Cordillera Blanca, Peru. III. Study of moraines and mass balances at Safuna.' *Journal of Glaciology* 18(79): 275-290

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

Meijer, RJ de; Smit, EM (1992) 'Some layman's observations on the stability of Tsho Rolpa, Nepal.' Internal report prepared for Netherlands-Nepal Friendship Association

Modder, S; van Olden, Q (1995) *Geotechnical hazard analysis of a natural moraine dam in Nepal*. Interim report prepared for the Free University of Amsterdam, The Netherlands

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

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

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

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

Müller, F (1959) 'Eight months of glacier and soil research in the Everest region.' In *The Mountain World 1958/59*, pp191-208. London: Allen and Unwin

Müller, F; Caflish, T; Müller, G (1977) *Instructions for compilation and assemblage of data for a World Glacier Inventory.* Zurich: Temporary Technical Secretariat for World Glacier Inventory, Swiss Federal Institute of Technology

Narama, C; Duishonakunov, M; Kääb, A; Daiyrov, M; Abdrakhmatov, K (2010) 'The 24 July 2008 outburst flood at the western Zyndan glacier lake and recent regional changes in glacier lakes of the Teskey Ala-Too range, Tien Shan, Kyrgyzstan.' *Natural Hazards and Earth System Sciences* 10: 647-659

NEA, DHM, BGR (2001) *Thulagi Glacier Lake monitoring report 2000*. Internal report prepared by Nepal Electricity Authority (NEA) and Department of Hydrology and Meteorology (DHM), Kathmandu, Nepal, and Federal Institute for Geosciences and Natural Resources (BGR) Hannover, Germany

Nurkadilov, LK; Khegai, AU; Popov, NV (1986) 'Artificial draining of an outburst-dangerous lake at the foot of surging glacier.' *Data of Glaciological Studies* 18: 220-221

Østrem, G (1966) 'Mass balance studies on glaciers in western Canada.' *Geographical Bulletin* 11 (7): 81-107

Østrem, G; Brugman, M (1991) *Glacier mass balance measurements,* National Hydrology Research Institute Science Report No 4. Saskatoon: NHRI

Østrem, G (2006) 'History of scientific studies at Peyto Glacier.' In Deymuth, MN; Munro, DS; Young, GJ (eds) *Peyto Glacier: One century of science,* National Hydrology Research Institute Science Report No 8, pp 1-23. Saskatoon: NHRI

Pant, SR; Reynolds, JM (2000) 'Application of electrical imaging technique for the investigation of natural dams: an example from the Thulagi glacial lake, Nepal.' *Journal of Nepal Geological Society* 22: 211-218

Rana, B; Shrestha, AB; Reynolds, JM; Aryal, R; Pokhrel, AP; Budhathoki, KP (2000) 'Hazard assessment of the Tsho Rolpa glacier lake and ongoing remediation measures.' *Journal of Nepal Geological Society* 22: 563-570

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

Reynolds, JM (2006) 'Role of geophysics in glacial hazard assessment, special topic.' *First Break* 24 (August): 61-68

RGSL (1994) *Hazard assessment at Tsho Rolpa, Rolwaling Himal, Northern Nepal*, Reynolds Geo-Sciences Ltd., Technical Report No: J9402.002 submitted to WECS. Kathmandu: WECS

RGSL (1996) *Final proposal for the lowering of the water level at Tsho Rolpa glacier lake, Nepal, to minimize potential GLOF Hazards*, Reynolds Geo-Sciences Ltd., Technical Report No: J9513.009 submitted to WECS. Kathmandu: WECS

RGSL (1997) *Assessment of the present status of the Tsho Rolpa glacier lake in Dolakha District of Nepal, supplementary report.* Reynolds Geo-Sciences Ltd., Technical Report No R9735.027 submitted to DHM. Kathmandu: DHM

RGSL (2000) *Special activity report for the ITA monsoon 2000 field visit*, Reynolds Geo-Sciences Ltd. report submitted to Tsho Rolpa GLOF Risk Reduction Project, Nepal

Richardson, SD; Reynolds, JM (2000) 'An overview of glacial hazards in the imalayas.' *Quaternary International* 65/66(1): 31-47

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

Sager, JW; Chambers, DR (1986) *Design and construction of the Spirit Lake Outlet Tunnel, Mount St. Helens, Washington*, Special Geotechnical Publication No 3. New York: ASCE

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

Sakai, A; Chikita, K; Yamada, T (2000) 'Expansion of a moraine-dammed glacial lake, Tsho Rolpa, in Rolwaling Himal, Nepal Himalaya.' *American Society of Limnology and Oceanography Inc.* 45(6): 1401-1408

Sakai, A; Yamada, T; Fujita, K (2003) 'Volume change of Imja glacial lake in the Nepal Himalayas.' In *International Symposium on Disaster Mitigation and Basin Wide Water Management,* pp556-561. Madrid: International Association of Hydraulic Engineering & Research (IAHR)

Sakai, A; Fujita, K; Yamada, T (2005) 'Expansion of the Imja Glacier Lake in the East Nepal Himalayas.' In Mavlyudov, BR (ed) *Glacier caves and glacial karst in high mountains and polar regions* (7th GLACKIPR symposium), pp 74-79. Moscow: Institute of Geography of the Russian Academy of Sciences

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

Shrestha, AB; Budhathoki, KP; Shrestha, RK; Adhikari, R (2004) 'Bathymetric survey of Tsho Rolpa Glacier Lake – 2002.' *Hydrology Journal of SOHAM* 1(1): 13-15

Stanganelli, M (2008) 'A new pattern of risk management: The Hyogo Framework for action and Italian practice.' *Socio-Economic Planning Sciences* 42: 92-111

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

Thorarinsson, S (1953) 'Some new aspects of the Grimsvotn problem.' *Journal of Glaciology* 2 (14): 267-275

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

Vuichard, D; Zimmermann, M (1986) 'The Langmoche flashflood, Khumbu Himal, Nepal.' *Mountain Research and Development* 6(1): 90-93

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

Wallén, CC (1949) 'The shrinkage of the Kårsa Glacier and its probable meteorological causes.' *Geografiska Annaler* 31(1-4): 275-291

Watanabe, T (1992) 'Human impact and landscape changes in the Nepal Himalaya.' Ph.D. Thesis, Department of Geography, University of California, Davis, USA

Watanabe, T; Ives, JD; Hammond, JE (1994) 'Rapid growth of a glacial lake in Khumbu Himal, Nepal: Prospects for a catastrophic flood.' *Mountain Research and Development* 14 (4): 329-340

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

Wavin Overseas, BV (1996) *Trial siphon at lake Tsho Rolpa, report on siphon installation (Tsho Rolpa/JVN).* Report submitted to WECS, Kathmandu, Nepal

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

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

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

WECS (1995a) *Data report, meteorological and hydrological data at Tsho Rolpa Glacier Lake, Rolwaling Himal, From June 1993 to May 1995,* WECS N551.489 DAT. Kathmandu: WECS

WECS (1995b) *Electrical resistivity exploration at Tsho Rolpa end moraine,* WECS N551.489 OYO. Kathmandu: WECS

WECS (1995c) *Preliminary report on the Thulagi Glacier Lake, Dhana Khola, Marsyangdi Basin,* WECS Report No 473, Seq. No. 2/3/170795/1/1. Kathmandu: WECS

WECS (1995d) *Report on Tsho Rolpa Glacier Lake field visit in Rolwaling Himal - Post-monsoon Season, 1995*, WECS N551.489 WAT. Kathmandu: WECS

WECS (1995e) *The debris flow and the hazard due to GLOF in the Rolwaling Valley, Nepal*, WECS N551.489 FUJ. Kathmandu: WECS

WECS (1996) *Report on the investigations of Tsho Rolpa Glacier Lake, Rolwaling Valley*. Kathmandu: WECS/JICA

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

Xu Daoming (1985) 'Characteristics of debris flows caused by outburst of glacial lake in Boqu River, Xizang, China, 1981.' *GeoJournal 17:569-580*

Xu Daoming; Feng Qinghua (1994) 'Dangerous glacier lakes and their outburst features in the Tibetan Himalayas.' *Bulletin of Glacier Research* 12: pp 1-8

Yamada, T (1992) *Report for the first research expedition to Imja Glacier Lake, 25 March to 12 April 1992,* WECS Report No 3/4/120892/1/1, Seq. No. 412. Kathmandu: WECS/JICA

Yamada, T (1993) *Glacier lakes and their outburst floods in the Nepal Himalaya*. Kathmandu: WECS

Yamada, T (1998a) *Glacier lake and its outburst flood in the Nepal Himalaya*. Monograph No. 1, March 1998. Nagoya: Data Centre for Glacier Research, Japanese Society of Snow and Ice

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

Zimmermann, M; Bichsel, M; Kienholz, H (1986) 'Mountain hazards mapping in the Khumbu Himal, Nepal, with prototype map, scale 1:50,000.' *Mountain Research and Development* 6(1): 29–40

Acronyms and Abbreviations

AIT	Asian Institute of Technology
BM	bench mark
CAREERI	Cold and Arid Regions Environmental and Engineering Research Institute
DDC	district development committee
DEM	digital elevation model
dGPS	differential global positioning system
DHM	Department of Hydrology and Meteorology
DNPWC	Department of National Parks and Wildlife Conservation
DWIDP	Department of Water Induced Disaster Prevention
EWS	early warning system
GIS	geographical information system
GLCF	Global Land Cover Facility
GLIMS	Global Land Ice Measurements from Space
GLOF	glacial lake outburst flood
GPR	ground penetrating radar
GPS	global positioning system
ICIMOD	International Centre for Integrated Mountain Development
Landsat	Land Observation Resources Satellite (LANDSAT)
NEA	Nepal Electricity Authority
NGO	non-government organisation
RS	remote sensing
UNU	United Nations University
VDC	village development committee
WECS	Water and Energy Commission Secretariat
WGS 1984	World Geodetic System 1984

About ICIMOD

The International Centre for Integrated Mountain Development, ICIMOD, is a regional knowledge development and learning centre serving the eight regional member countries of the Hindu Kush-Himalayas – Afghanistan, Bangladesh, Bhutan, China, India, Myanmar, Nepal, and Pakistan – and based in Kathmandu, Nepal. Globalisation and climate change have an increasing influence on the stability of fragile mountain ecosystems and the livelihoods of mountain people. ICIMOD aims to assist mountain people to understand these changes, adapt to them, and make the most of new opportunities, while addressing upstream-downstream issues. We support regional transboundary programmes through partnership with regional partner institutions, facilitate the exchange of experience, and serve as a regional knowledge hub. We strengthen networking among regional and global centres of excellence. Overall, we are working to develop an economically and environmentally sound mountain ecosystem to improve the living standards of mountain populations and to sustain vital ecosystem services for the billions of people living downstream – now, and for the future.

Glacial Lakes and Glacial Lake Outburst Floods in Nepal – Additional Material

DVD with full report and additional material
(GIS database, maps, photos, video clips)

If the DVD is missing, please write to **distri@icimod.org** for a copy

Supported by

NORWEGIAN MINISTRY
OF FOREIGN AFFAIRS

Sida

International Centre for Integrated Mountain Development
GPO Box 3226, Kathmandu, Nepal
Tel +977-1-5003222 **Fax** +977-1-5003299
Email info@icimod.org **Web** www.icimod.org

ISBN 978 92 9115 193 6

LCCN 2011-312004